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Practical Aspects in Optimisation of Radiological Protection in Digital Radiography, Fluoroscopy, and CT

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Guest Editorial

OPTIMISATION IN MEDICAL IMAGING: A PRACTICAL GUIDE

Optimisation of radiological protection is one of the most challenging activities for the new imaging technologies in medicine. It requires involvement of the full imaging team of radiologists, radiographers, and medical physicists, but also the input of technical personnel from the vendors and, in part, the hospital management. The new technologies require a continuous interaction with the vendor representatives, especially after updates of software and hardware of the x-ray systems. The use of dose management systems or automated exposure information systems in optimisation may also be helpful in improving optimisation and radiation safety aspects, and is being integrated as part of the quality programme in many radiology departments.

One of the advantages, but also one of the challenges, of digital imaging is that it is possible to select the quality of the images for a clinical task or clinical indication. The term 'image quality' should also be understood as 'diagnostic information' when several series of images are obtained during a procedure. More quality in the images, or more diagnostic information, requires the use of a greater radiation dose. Many physics parameters are involved in the different operational protocols (kV, mA, pulse time, filtration, geometry, image acquisition modes, etc.), and specific training for optimisation is required for the new x-ray systems. In addition, patient size, the ability of patients to cooperate (especially in paediatrics), and some specific situations (e.g. pregnant patients) may require particular operational protocols. The priority should always be to obtain the required diagnostic information for the clinical task, with the minimum radiation dose for the patient.

Consideration of occupational protection should also be one of the aspects to be integrated into the full optimisation process for some interventional procedures, as recommended in *Publication 139* on 'Occupational radiological protection in interventional procedures' (ICRP, 2018). Other non-radiation-related risks (e.g. use of contrast agents, medications, sedation/anaesthesia, etc.) should also be considered for some optimisation actions.

The recommended operational protocols may be suggested by the vendors initially, but they need to be tested and, in some cases, adapted for individual patients. In these cases, the roles of radiologists (or other medical doctors involved in the

imaging procedure), radiographers, and medical physicists are especially important. Radiation dose may be fairly easy to measure (or calculate), and modern x-ray systems offer this information, but the image quality or diagnostic information needed for the clinical tasks may be more difficult to establish in some cases.

Sometimes, several, or even many, images are necessary, using different acquisition modes (especially for interventional procedures). The impact of new technologies and post-processing of the images may improve the diagnostic information obtained from the images considerably. Radiologists should know the level of radiation dose involved in the different operational protocols when deciding the required image quality (or amount of diagnostic information).

Initial and continuing training for optimisation strategies are relevant aspects to be integrated in radiology departments. The cooperation of the technical staff of the vendors should also be considered.

This publication contains detailed recommendations and will be used in many hospitals to help in the practical aspects of optimisation for the three most relevant imaging modalities: digital radiography; fluoroscopy/interventional radiology; and computed tomography. Two additional short chapters are dedicated to paediatric procedures and examinations of pregnant patients. This publication contains the main points for every chapter, summarised conclusions, and two annexes on ‘Dose quantities and units’ and ‘Automated exposure information reporting systems’.

This publication discusses the three main areas for good management of optimisation: (i) collaboration between radiologists and other physicians, radiographers, medical physicists, and managers; (ii) access to the appropriate methodology, technology, and expertise; and (iii) provision of organisational processes to ensure that equipment performance tests, patient dose surveys, and reviews of protocols are undertaken at appropriate time intervals.

The needs for proper initial education and ongoing training of staff on the operation of equipment, both of which are crucial in achieving optimisation, are highlighted. Aspects of artificial intelligence and the advantages of iterative reconstruction for computed tomography should form part of the training.

This publication suggests three levels of optimisation – basic, intermediate, and advanced – with preliminary planning in order to start the process. Optimisation is not a static process. It requires constant attention with frequent monitoring of performance, feedback of experience, and regular review. Medical physicists should follow the values of patient dose indicators for a periodic comparison with diagnostic reference levels (DRLs), and new imaging protocols (especially with new x-ray systems or new software) could require new local DRLs to be set. This is much easier

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when a dose management system or automated exposure information system is available.

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ICRP, 2018. Occupational radiological protection in interventional procedures. ICRP Publication 139. Ann. ICRP 47(2).

PRACTICAL ASPECTS IN OPTIMISATION OF RADIOLOGICAL PROTECTION FOR DIGITAL RADIOGRAPHY, FLUOROSCOPY, AND CT

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Abstract—Digital radiology is playing an increasingly important role in medicine worldwide. The use of computed tomography (CT) has risen dramatically in recent decades, and makes up approximately half of the population dose from medical exposures in many parts of the world. In addition, ever more complex interventional procedures guided by fluoroscopy are replacing more invasive surgical techniques, thus substituting risks from surgery with lesser ones from radiation. These radiological techniques provide significant health benefits, but the associated radiation dose levels need to be kept commensurate with the benefit accrued. Key factors in achieving this are ensuring that examinations are only carried out when they can contribute to management of a patient's condition, and that the radiological protection aspects for all exposures are optimised. The latter is the subject of the present publication.

Digital imaging data contribute versatility in image acquisition, post-processing, and presentation, and provide opportunities for optimisation. However, unlike their analogue equivalent, images acquired digitally may not provide an indication that a dose is too high or images are not collimated, so there are new problems that have to be addressed. In *Publication 154*, three fundamental requirements for taking the optimisation process forward were described: (i) the need for collaboration between radiologists, other radiological medical practitioners, radiographers/medical radiation technologists, medical physicists, and managers; (ii) access to the appropriate methodology, technology, and expertise; and (iii) provision of organisational processes which ensure that tasks, such as equipment performance tests, patient dose surveys, and reviews of protocols, are carried out and acted upon. A high-level requirement is the integration and use of decision sciences, and harmonisation of these optimisation processes across multi-specialty clinical teams and equipment types within healthcare systems.

This publication contains information on practical methods needed to carry optimisation forward for different imaging techniques: radiography, fluoroscopy (and fluoroscopically guided interventional procedures), and CT. Many features of digital equipment allow dose levels to be reduced while still maintaining adequate image quality for the clinical task. Staff need to understand the relationship between the different selectable options to use the features effectively. However, there is a wide range in available equipment and training around the world. Provision ranges from clinics with simple radiographic units to specialist hospitals with complex state-of-the-art equipment. Some countries have established communities of medical physicists, while in other countries, there is little or no medical physics support. This presents challenges in communicating requirements for optimisation. This publication addresses these challenges by providing information for facilities within broad categories linked to optimisation arrangements already in place: Level D – preliminary; Level C – basic; Level B – intermediate; and Level A – advanced. It is hoped that through this approach, radiology teams will be able to plan strategies for introducing optimisation techniques that are appropriate for their own facilities and equipment.

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Keywords: Digital radiography; Fluoroscopy; Fluoroscopically guided interventions; Computed tomography; Optimisation; Paediatric radiology; Pregnant patients

MAIN POINTS

- **Optimisation of radiological protection in diagnostic imaging and image-guided procedures should be built on collaboration between radiologists or other radiological medical practitioners, radiographers/medical radiation technologists, and medical physicists, and developed from the initial level (Level D) when a facility is set up, to the basic requirements (Level C), through the intermediate level (Level B), to the advanced processes of Level A, as set out in this publication.**
- **Exposure factors for digital radiography should be established for different clinical tasks and patient characteristics, making use of automatic exposure control devices and possible use of different filtration options, especially for paediatric exposures, with exposure indices and image collimation monitored.**
- **Exposure factor selection programmes for fluoroscopy should be configured to provide the diagnostic information required for the range of clinical tasks at commissioning, and dose and image quality performance should be monitored through regular quality control. Management of occupational protection for interventional procedures should be integrated with patient protection.**
- **Development of protocols for computed tomography to give a level of image quality that has been agreed among the professionals involved requires consideration of the interdependence of exposure parameters, proper application of automatic tube current modulation, and iterative or deep-learning-based reconstruction to enable appropriate, often lower, dose settings to be used.**
- **Paediatric protocol optimisation requires an understanding of clinical indications, patient sizes, and the ability of patients to cooperate. Particularly for interventional procedures, occupational protection should be managed in an integrated manner with patient protection. Protocols for pregnant patients require optimisation to reduce doses for both the mother and conceptus.**

1. INTRODUCTION

1.1. Background

(1) The principle of optimisation has been a major part of radiological protection thinking for three decades (ICRP, 1991), and is key to effective use of medical imaging. Optimisation in relation to medical imaging requires provision of clinical images for individual patients that are of sufficient quality to ensure accurate and reliable diagnoses, in order to enable informed care decisions to be made. In addition, the radiation doses used in acquiring such clinical images should be adjusted so that, while being adequate to produce the images, they are minimised to the level appropriate to the applied imaging technology. This publication deals with the practical aspects of optimisation relating to the different digital radiology modalities.

(2) *Publication 73* identified two areas in which optimisation of protection should be applied in medicine: (i) the design and construction of equipment and installations; and (ii) the day-to-day methods of working (ICRP, 1996). Optimisation is not a single action, and many aspects need to be in place before an x-ray facility can even embark on the road to achieving optimisation. These are not straightforward and have become quite complex in the healthcare environment. Proper initial education and ongoing training of staff on the operation of equipment is crucial to starting the process (Vassileva et al., 2022). However, this needs to be coupled with arrangements for the ongoing monitoring, review, and analysis of imaging performance, that can be used to improve overall effectiveness gradually. Optimisation of medical imaging requires continuing development of knowledge, skills, competencies, and experience of all professionals involved in the imaging process.

(3) *Publication 154* (ICRP, 2023) sets out three building blocks on which strategies for achieving optimisation should be built. The first cornerstone is professionalism, namely collaboration between the professionals involved in diagnostic imaging (typically radiologists or other radiological medical practitioners, radiographers/medical radiation technologists, and medical physicists) working together as a team within an organisation that provides a structure to facilitate the process (N.B. The term ‘radiographer’ will be used rather than ‘medical radiation technologist’ throughout this publication). The radiologist or other radiological medical practitioner can judge whether the image quality is sufficient for the diagnostic or interventional objective, the radiographer should know the practical operation and limitations of the equipment, and the medical physicist should understand the physical principles behind image formation and be able to perform and interpret measurements of dose and image quality. It should be noted that, in some countries, health professionals other than radiological medical practitioners may be trained to interpret images for specific applications. The referring clinician, radiological medical practitioner, and radiographer work together to understand the ability of the patient to undergo an

imaging examination. The increasing technical and computational complexity in radiology equipment and applications underlines the importance of this multi-professional collaboration and dependency on the combined knowledge of different professionals.

(4) The second building block is concerned with methodology. It encompasses the knowledge and skills required, in combination with the instruments and test objects needed to evaluate the performance of imaging equipment. Digital imaging carries the potential for images to be obtained with a wide range of exposures, enabling levels to be adapted to the diagnostic requirements of particular examinations. Moreover, new features and techniques that can improve image quality and potentially enable clinical images to be obtained with lower patient doses are becoming available all the time. Almost inevitably, these features introduce additional complexities. If they are not deployed effectively because of limited awareness of their mode of operation, the doses received by patients may be far from optimal.

(5) The third building block is concerned with processes. There is a requirement to put processes in place to manage the activities which ensure that a quality assurance (QA) programme is established in order to maintain performance. An example would be the audit of patient doses against local, national, or regional diagnostic reference levels (DRLs) (ICRP, 2017). Results should be combined with clinical assessments to feed into the development of examination protocols that are optimised for the clinical purpose. The management systems should confirm that measurements and assessments are made, that protocols are reviewed regularly, and that all available data from clinical use and performance measurements are used in making adjustments to protocols and to identify areas for practice improvement.

(6) There are large variations in the levels of knowledge, skills, and competencies, and the availability of radiology professionals between different clinics, hospitals, and countries. There is also a wide range in available equipment, resources, and expertise around the world. Radiology service provision ranges from clinics in remote locations with simple radiographic units to specialist hospitals with multiple computed tomography (CT) scanners and interventional units. In some countries, there are established communities of medical physicists, while in other countries, medical physics support is in short supply or even non-existent, and funding to expand this may be limited. The range in available resources presents significant challenges when communicating a harmonised route through the various steps in the optimisation process, as facilities will be at different stages in the process and have different arrangements in place. Therefore, priorities for appropriate action will depend on the next stage in their development.

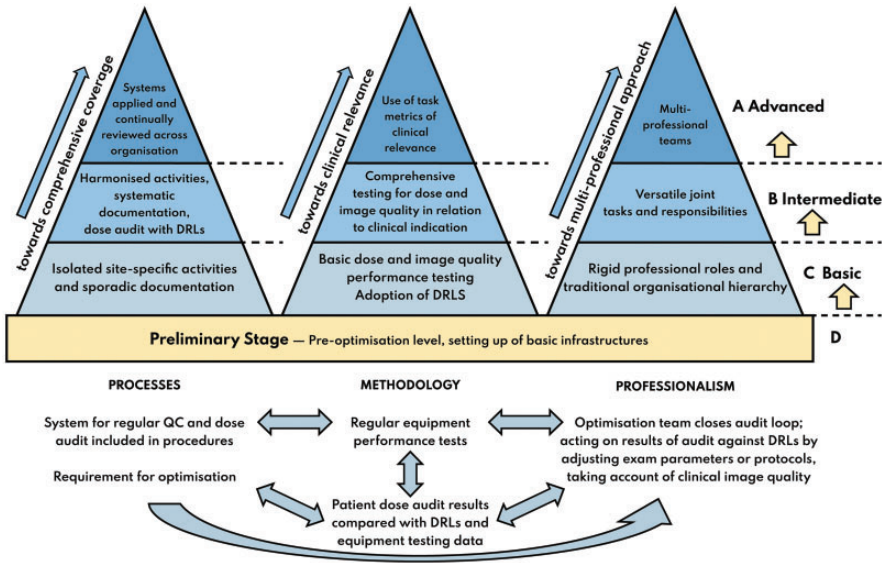


Fig. 1.1. The three main components in the development and maturation of optimisation: processes, methodology, and professionalism. The levels represent different stages in achievement moving upwards from D, through C and B, towards A. Level D represents a baseline infrastructural level as a prerequisite for initiation of the optimisation process. Levels A, B, and C set out the arrangements that will be in place for each component when that level is achieved. If the support of medical physicists is limited, it will be difficult to reach the intermediate (B) or advanced (A) levels of optimisation. This is a critical issue in countries where medical physicists are not commonly included as professionals in the radiology ‘core’ team, so only the basic (C) level can be reached. The lower section shows the stage after the adoption of diagnostic reference levels (DRLs) (whether local, national, or regional) has occurred. Processes are in place to require both regular quality control (QC) tests, including checks of image quality, and dose audit against the DRLs, and use of the information obtained in optimising protocols and providing feedback, indicated by the arrows. Boxes in later sections contain advice on requirements in terms of practices to achieve levels relating to different modalities. Source: Colin Martin, University of Glasgow, UK.

(7) This publication attempts to address these challenges by providing detail for facilities, within broad categories for levels of optimisation, divided into Level D – preliminary (before actions have been taken to start the process of optimisation); Level C – basic; Level B – intermediate; and Level A – advanced, as described in *Publication 154* (ICRP, 2023) (Fig. 1.1). Advice and training from experts through the International Atomic Energy Agency (IAEA) and other international organisations is already providing assistance in putting building blocks in place in nations where optimisation is at Levels D and C. Sometimes, achievement of specific aims, such as the setting of national DRLs, can become the main goal when a country starts to consider requirements for optimisation, and this can obscure the long-term

objectives. *Publication 154* attempted to set out guidance to assist in the review of arrangements that are in place in different departments, so that strategies can be developed to assess requirements for the next stage in optimisation. Such strategies can be used in planning arrangements for developing an optimisation programme that will be carried forward into the future.

(8) There will be continual development in equipment and software technologies, and the necessary knowledge, skills, and competencies of the radiology professionals that should feed into a process of steady improvement. Career-long commitment to training should be ensured through government and/or employer resources, accreditation of educational programmes, and standard initial and periodic competency assessments (ICRP, 2009; Vassileva et al., 2022). Optimisation is not a static process to be ignored and forgotten once a particular goal has been achieved; it requires constant attention with frequent monitoring of performance, feedback of experience, and regular review to provide continual refinement of the service to the patient (ICRP, 2006).

(9) Before going on to discuss optimisation in the context of digital radiology in more detail, something should be said about the appropriateness of the term ‘ALARA’ (as low as reasonably achievable) that is used in relation to optimisation of protection for occupational and public exposure situations. The term is not appropriate when referring to medical uses of radiation as it omits an important component, namely the benefit that is derived by the patient from the exposure. As stated in *Publication 120*, ‘the entire concept [of optimisation applied to medical exposures] implies keeping patient exposure to the minimum necessary to achieve the required medical objective (diagnostic or therapeutic)’ (ICRP, 2013a). In diagnostic imaging and x-ray-guided interventions, it means that the number and quality of images are adequate to obtain the information needed for diagnosis or intervention (Samei et al., 2018). Use of the abbreviation ‘ALARA’ alone and out of this context may be misleading and raise unnecessary controversy.

1.2. Practical techniques for optimisation in digital radiology

(10) Technological innovations that have the potential to provide a higher degree of optimisation are being implemented continually. When new software is added to existing equipment, it is essential that adequate training is provided to end users. This training is typically provided by the vendor application specialist, but the medical physicist and senior radiographers may also contribute to local training. Assessments of aspects of image quality as well as radiation dose are now used in controlling exposure levels, increasing the importance of combined parameter settings for optimisation. As the level of sophistication develops, the variety and complexity of procedures that are possible increases. To make full use of new features, the performance of equipment needs to be monitored and analysed, and examination protocols need to be refined as more experience is gained.

(11) Operation of all digital radiology imaging involves the need to understand the interdependence of patient dose and image quality. This publication will not deal with these aspects in detail, except where they relate to performance of a particular type of equipment. Instead, readers are directed to *Publication 154* that contains sections dealing in more depth with considerations of equipment installation and life cycle, dose audit, and image quality analysis (ICRP, 2023), and to *Publication 135* in relation to the setting and use of DRLs (ICRP, 2017).

(12) As technology develops, sophisticated imaging equipment (such as CT scanners) is being acquired in countries where there may not be the degree of professional expertise available that potentially exists in nations where such equipment has been available for some years. Paying full attention to both the proper training of staff and the provision of instructions on techniques for optimisation linked to new equipment is therefore becoming ever more important. The present publication provides guidance on techniques for optimisation linked to different imaging modalities in digital radiology. It identifies components that will be important for facilities implementing optimisation, as they move up the levels referred to above, from D to C (basic), B (intermediate), and A (advanced). The stage of optimisation that different facilities have achieved will depend on the numbers of staff available, their training and experience, and the equipment available. In order to assist in the identification of the arrangements for optimisation that facilities at different levels might be expected to have and those they need to develop, a box is included at the end of each modality section listing the arrangements that should be in place at the different levels. Facility staff and managers should use these lists as a guide to evaluate departments, and identify aspects that it would be appropriate to focus on for their next stage of development.

(13) This publication is aimed at radiologists, other radiological medical practitioners such as interventional cardiologists, radiographers, medical physicists, vendors, and radiology management. Parts are also intended for use by other clinicians, relevant expert societies/organisations, and regulators. There will be parts that are more suitable for one group or another group. For example, in Section 2 on radiography, some parts deal with optimisation as part of the day-to-day work of the radiographer. On the other hand, there are parts of Sections 2, 3, and 4 that deal with aspects of equipment performance set up during commissioning, which are of most relevance to medical physicists, but that need to be taken forward in discussion with radiological medical practitioners and radiographers. There are also approaches for interventional procedures in Section 3, which will be of prime interest to radiologists and other radiological medical practitioners performing them, but also of relevance to other groups. Facility managers and regulators should understand the optimisation processes for different populations and clinical needs. Moreover, they should understand the need for adequate and sufficiently trained human resources as a prerequisite for putting a successful optimisation process in place. Indeed, without enough working hands and minds, the practical optimisation undertaken will inevitably remain at a superficial level.

1.3. The role of artificial intelligence in optimisation

(14) Interest in artificial intelligence (AI) as a way of improving the value of medical images in early diagnosis and optimising patient management is the focus of many research studies at the present time (Ranschaert et al., 2019; ICRP, 2023). However, there are many technical, legal, and ethical challenges to be solved before AI can become a robust tool that can be widely adopted in clinical practice (Sahiner et al., 2019). Machine learning (ML) is a form of AI methodology involving the development of computer programs that can find complex patterns, which might represent lesions or other features, within complex data sets. ML has been developed to learn from data without being programmed explicitly. A model or mathematical algorithm is trained on image data sets to enable it to predict an outcome for new patient data similar to that given by a human expert.

(15) Deep learning (DL) is a subset of ML and applies deep neural networks (Suzuki, 2017; Esteva et al., 2019). DL has become feasible in the last decade due to the enormous number of medical images and other big data now being produced, and advancements in computer hardware and graphics processing. To be successful, DL typically (in supervised learning) requires massive annotated datasets for DL model training, validation, and testing. The DL methods are already yielding promising results in medical imaging related to many diagnostic tasks, such as lesion or tissue localisation, segmentation, classification, and prediction of clinical outcomes, and are being used in CT image reconstruction or restoration. Specific image quality improvements are also feasible with DL methods (Maier et al., 2019; Nam et al., 2021).

(16) AI methods can enable reductions in patient dose through automation and optimisation of data acquisition processes, including patient positioning and acquisition parameter settings (McCullough and Leng, 2019), and optimisation of the radiological chain. Image quality measurement, classification, and grading, in addition to patient-specific dosimetry, may be achieved using an ML/DL approach and may ultimately replace traditional methods such as model observers for image quality assessment and Monte Carlo simulations for dosimetric calculations (Samei and Krupinski, 2018; Inkinen et al., 2022; Maier et al., 2022). Although digital radiology is potentially well suited to DL, its application in diagnosis requires high-quality, high-volume image and outcome data, and the number of potential clinical scenarios is huge. A major challenge is in access to sufficient annotated (if supervised learning is applied) and representative training data, which is a fundamental prerequisite if sufficient robustness is to be achieved in making AI methods more generally applicable and properly validated to the clinical setting. This will require not only regulatory approval of algorithms and procedures, but also measures in hospitals to ensure that the methods are appropriate for local patient cohorts. Assistance from professional bodies is likely to be required in carrying this out. AI will be an elemental part of radiological imaging in the future, although it will take time to reach clinical implementation and integration from the research and development projects.

1.4. Previous and upcoming ICRP publications on digital radiology

(17) In the last two decades, ICRP has prepared publications focusing on the technical requirements for optimisation in radiography, fluoroscopy, and CT. These publications have provided practical methodologies for optimisation to address the needs arising from the development of new technologies.

(18) Digital radiography enables the image data to be processed to give images optimised for viewing, but makes high (and low) exposures more difficult to identify. ICRP prepared *Publication 93* to facilitate the transition from film/screen to digital radiography (ICRP, 2004). Section 2 of the present publication extends the advice given, and deals with the pitfalls in optimisation during the routine use of digital radiography.

(19) The rapid development of fluoroscopically guided interventions had led to the appearance of cases of tissue reactions in patients in radiological imaging. *Publication 85* on guidance to avoid radiation injuries was published to address this risk (ICRP, 2000b). *Publications 117* and *120* provided further guidance following developments in the use of fluoroscopically guided procedures by other specialties outside the imaging department (ICRP, 2010) and the increased use of imaging in cardiology (ICRP, 2013a). Section 3 of the present publication augments the measures described for general optimisation of patients' exposures in these publications, but will not deal with the risk of tissue reactions to the same depth.

(20) *Publication 139* covered occupational radiological protection for interventional procedures (ICRP, 2018b). As such, the present publication does not deal with occupational exposure issues in any depth, but emphasises that occupational protection should be managed in an integrated approach with patient protection.

(21) *Publications 87* and *102* covered optimisation in terms of managing patient dose in conventional single-slice and multi-slice CT (ICRP, 2000c, 2007a). However, there have since been enormous developments in CT hardware and software, such as iterative reconstruction (IR) which was not discussed in the earlier publications, and automatic tube current modulation for which the software has evolved since the previous publications. Section 4 of the present publication provides extensive discussion of opportunities for optimisation in CT, and the risks if potential dose reduction features are not fully understood and used incorrectly. In addition, *Publication 129* (ICRP, 2015) discussed the application of cone beam on C-arm fluoroscopic and interventional units. ICRP Task Group 117 will provide a publication on CT optimisation when used with positron emission tomography (PET) and single photon emission tomography (SPECT) in hybrid imaging (ICRP, 2024).

(22) The specific needs and challenges in diagnostic and interventional procedures of paediatric patients, for whom the risks of radiation exposure are greater, were addressed in *Publication 121* (ICRP, 2013b). The optimisation methods for paediatric imaging are developed further in Section 5 of the present publication. ICRP set out the approach to medical exposures on pregnant patients in *Publication 84* (ICRP, 2000a) to take account of the higher risk of childhood leukaemia resulting

from fetal exposures. Section 6 of the present publication considers the approach to optimisation of exposures during pregnancy in terms of minimising the dose to the embryo/fetus and assessing the dose delivered.

(23) The present publication covers the application of digital radiology to medical diagnostic and interventional applications. The content replaces material in *Publication 93* on technical issues in digital radiology (ICRP, 2004), and *Publications 87* and *102* on CT (ICRP, 2000c, 2007a), and supplements material in *Publications 85*, *117*, and *120* (ICRP, 2000b, 2010, 2013a) linked to specific applications of fluoroscopy and interventional procedures, *Publication 121* (ICRP, 2013b) on paediatric imaging, and *Publication 135* (ICRP, 2017) on DRLs. This publication does not include mammography, for which detailed specialist texts are available (IAEA, 2005, 2021, 2023a; AAPM/EFOMP, 2023), the application of imaging in radiotherapy, which will be covered in a future publication (ICRP Task Group 116), or dental radiology that is practised by a different group of medical professionals and for which specialist texts are also available (White and Pharoah, 2013; NCRP, 2019a; IAEA, 2022c).

(24) There are management tools to facilitate workflow that accompany digital imaging. These make tasks such as storage and transfer of image data, manipulation and merging of images, and recording of exposure details easier to carry out. The tools, which include radiology information systems, picture archiving and communication systems (PACS) and dose management software, are described in Annex B.

2. DIGITAL RADIOGRAPHY

(25) Key points in this section:

- Digital radiography facilitates the storage and transfer of image data and recording of exposure details, as well as offering more flexibility in exposure. Digital radiography has a wider dynamic range than film, allowing for adjustment of images after exposure. As a result, it is the noise level and image contrast that set the limits on image quality, in addition to spatial resolution.
- Selection of tube potential is a compromise between competing requirements, such as contrast and penetration, and appropriate combinations of tube potential and mAs should be established for different anatomical regions and patient characteristics linked to the clinical question to be answered.
- Grids are used for most adult radiography examinations, but may be dispensed with for examinations of small children or thin body parts (10–12 cm). ‘Virtual grid’ software can be useful where there are practical difficulties in mobile radiography, but will not replace the physical grid in all situations.
- Additional copper filters (0.1–0.3 mm) can give reductions of 20–50% in effective dose with tube potentials of 70–80 kV by removing low energy photons, and are recommended routinely for paediatric examinations.
- Automatic exposure control (AEC) devices should be calibrated to suit the characteristics of the detector, and can be set up to maintain a constant exposure index (EI) or signal-to-noise ratio (SNR) for a particular clinical task. The initial setting is crucial in determining exposure levels, and all chamber combinations should be tested regularly with phantoms representing a range of patient thicknesses.
- The target exposure index (EI_T) represents the optimal exposure for a particular body part being imaged, patient characteristics, and imaging task. EI_T values should be determined by the optimisation team and will depend on the noise level required. The deviation index (DI) based on the EI_T should be monitored as part of the quality control (QC) programme
- The central importance of collimation on patient dose and image quality should be emphasised throughout radiographer training. Suboptimal practice should be identified through regular audit of kerma-area product (KAP) against expected good practice values.
- The use of patient shielding during x-ray-based diagnostic imaging should be discontinued as routine practice.
- Data on rejected images should be collected and analysed regularly. Reject and retake rates should be calculated, and quality improvement actions should be taken when they rise above a pre-determined threshold. Reasons for rejects and retakes should be used to steer improvements in working methods.
- Acceptance testing and commissioning are crucial to ensure that new equipment is performing optimally. After commissioning, medical physicists and radiographers should work together to establish a local QC/QA programme.

- **Radiographers, radiologists or other radiological medical practitioners, and medical physicists should collaborate to identify the most appropriate processing algorithms for reporting radiographs.**

2.1. The digital radiography system

(26) Radiography is the fundamental radiological imaging process, and is in widespread use throughout the world in different types of facilities. The move from film to digital imaging has simplified the sharing of images, and reduced running costs and material consumption. Digital radiography facilitates the storage and transfer of image data and recording of exposure details, as well as offering more flexibility in exposure, enabling levels to be adapted to the diagnostic requirements of particular examinations.

(27) There are typically multiple radiography rooms in larger hospitals, and smaller hospitals and clinics that have their own radiographic room or mobile unit. Thus, there are broad ranges in facilities using radiography, with different radiographic equipment and varying levels of experience for personnel who carry out the procedures. The setting up of a new installation requires careful planning by a team of radiological professionals, and arrangements for this are described in Section 2 of *Publication 154* (ICRP, 2023).

(28) Digital radiography systems have significantly broader dynamic ranges than film, and the grey levels in the displayed image can be adjusted for optimal viewing through post-processing independent of exposure (Fig. 2.1). As a result, it is the noise level and image contrast that set the limit on image quality, in addition to spatial resolution.



Fig. 2.1. Presentations of the same chest image using different post-processing look-up tables, with an underexposed image on left, overexposed image in middle, and optimised image on right. Source: Dean Pekarovic, University Medical Centre Ljubljana, Slovenia.

(29) The digital radiography systems available are described briefly in Box 2.1. In many hospitals, the first stage in the introduction of digital radiography is the installation of computed radiography, as this can be used with existing x-ray equipment, the film/screen cassette simply being exchanged for a computed radiography cassette. However, the x-ray unit AEC system should be recalibrated to suit

the characteristics of the computed radiography or direct digital radiography detector – a point that is often overlooked (ICRP, 2004; Doyle and Martin, 2006; IAEA, 2015; Moore et al., 2019). Full digital radiography systems offer more detailed pre-installed protocols, including not only tube kV and mAs selection, but source to image receptor distance (SID), additional filtration, field of view (FOV), position of image receptor, use of radiographic grid, and post-processing tools.

(30) Digital systems allow for digital archiving, and in many hospitals, digital images are held centrally on PACS systems and images viewed on workstations. As a result, radiologists or other radiological medical practitioners and radiographers find themselves in separate rooms. This can be detrimental to regular communication, education, and QA, and this should be borne in mind when new facilities are being set up. Regular exchange of information between radiographers and radiological medical practitioners, and with medical physicists where available, on what can be improved, with changes being implemented, facilitates continuous improvement in radiographic technique. This link is crucial, especially in relation to specific clinical indication examination protocols (Image Wisely, 2022a, Case 4).

(31) Computed radiography and digital radiography images are reviewed by radiological medical practitioners on diagnostic quality displays [Digital Imaging and Communication in Medicine (DICOM) calibrated], but the display on the operators' console may not be of a similar quality, and illumination conditions in the acquisition room may not be ideal. Images on diagnostic displays may be larger in size, with a higher pixel count, more greyscale levels, and better image reproduction. If images viewed at the console are of poorer quality, it will be more difficult to appreciate subtle effects or even artefacts that might be corrected. For effective control of digital radiography systems, radiographers should have access to review diagnostic quality displays, on which all exposure parameters are visible, ideally at the operator console, with adaptable room illumination conditions with the capability for dimming.

Box 2.1. Digital radiography technology

Computed radiography: The image is stored on a photo-stimulable phosphor (barium fluorohalide or comparable) plate and converted to digital form later using an image plate reader.

Digital radiography: The image recorded is stored directly in a digital detector containing an array with phosphors or photodiodes that convert x-ray energy into light or an electrical signal that can be recorded (ICRP, 2004; EC, 2004; IPREM, 2010). The types of system can be subdivided into indirect x-ray capture digital radiography and direct x-ray capture digital radiography:

- Indirect digital radiography systems contain a phosphor plate backed by a diode array. Caesium iodide imaging plates used in many digital radiography systems have thicker phosphor layers with needle-shaped crystals, and are substantially more sensitive than systems using gadolinium oxysulphide or other phosphors (ACR/AAPM/SIIM/SPR, 2022).
- Direct digital radiography systems comprise a conductive layer of a semiconductor, such as selenium or cadmium telluride, backed by an array of electrodes. X-ray photons are converted into electron-hole pairs in the semiconductor (Queiroz et al., 2020).

(32) The measurable quantities used to monitor patient dose in radiography are incident air kerma at patient entrance surface (IAK, K_i); entrance surface air kerma ($ESAK, K_{a,e}$), which may be calculated from exposure factors or measured with dosimeters; and kerma-area product (KAP, P_{KA}), measured by a meter attached to the output port of the x-ray unit or derived from a look-up table. These are listed in Annex A and more information on their use is given in *Publication 135* and *154* (ICRP, 2017, 2023).

(33) As the greyscale level is optimised in digital radiography, the primary feedback on exposure, unless a KAP meter is fitted, will be through the EI (Section 2.2.3; IEC, 2008; AAPM, 2009; Dave et al., 2018). The EI is a measure of radiation incident on the image receptor (see Section 2.2.3), and so reflects the noise levels present in the image. Although the EI will be related to the KAP values, it should not be considered as a surrogate for dose (Annex A). Monitoring of the EI, together with periodic auditing of KAP or ESAK, is essential to keep track of any changes in exposure conditions and dose level (Cohen et al., 2011; ICRP, 2017; AAPM, 2018). The EI will vary with the type of examination (Jamil et al., 2018), but will vary less with patient size than measured dose quantities, and deterioration in the performance of computed radiography cassettes with time will be apparent through change in the EI.

(34) The change from film to digital technology offered an opportunity to optimise patient dose. However, there was often a tendency for the dose to rise or remain the

same, rather than fall. The transition requires a critical examination of procedures, technical issues, and estimation of doses, together with comprehensive training in radiographic techniques, followed by regular QC tests, to ensure that effective use is made of the system (ICRP, 2004; IAEA, 2015).

2.2. Optimisation of exposure factors and radiation quality

2.2.1. Tube potential and mAs

(35) X-ray beams used for medical imaging contain photons with a wide range of energies determined by the x-ray tube potential and filtration. Lower energy x-ray photons provide better contrast between tissues of differing compositions, but are more heavily absorbed. Higher energy photons do not interact as strongly in tissue, and tend to give more scattered radiation and poorer contrast, but they will penetrate more deeply through tissue. The maximum energy is determined by the tube potential. The product of the tube current and exposure time, usually referred to as mAs, controls the number of photons emitted from the x-ray tube. For a given tube potential, the mAs will determine the number of photons reaching the image receptor, and so the level of quantum noise in the image. If a higher tube potential is used for a particular projection, the mAs can be reduced to give a similar exposure at the image plate with a lower patient entrance dose. However, the contrast will decrease and the amount of background scattered radiation will increase, so the choice of tube potential is a compromise between the competing requirements (Martin, 2007; ICRP, 2023). Appropriate combinations of kV and mAs should be established for different anatomical regions and patient characteristics, and linked to the clinical question to be answered. As digital image parameters can be adjusted, there is a potential to recover some of the loss of contrast when increasing the kV.

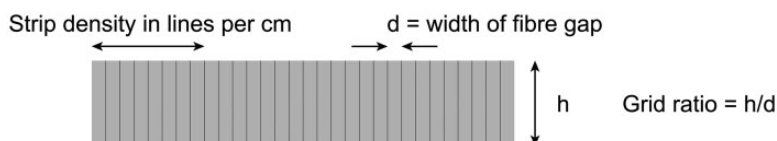
(36) The choice of tube potential is a crucial component of optimisation in radiology. Tube potentials of 70–90 kV will generally be used for exposures of the trunk, with values being increased for larger patients; 50–60 kV will be used for extremities; and 55–70 kV will be used for premature infant, neonatal, and infant chest/abdomen radiography. However, the tube potential values are higher (120–140 kV) when a grid is used for chest images on fixed radiographic units (anti-scatter grid of at least 10:1, preferably 12:1) (ACR/AAPM/SIIM/SPR, 2022) (Box 2.2).

(37) The highest tube potential within the optimal range for the position should be used, coupled with the lowest mAs needed to provide an adequate exposure to the image receptor (Herrmann et al., 2012). Examples of ranges of tube potential recommended for imaging different parts of the body, technique factors, and expected dose levels for a range of imaging tasks are given in Table 2.1. The values in the table are approximate and are included to provide guidance on levels that might be expected, rather than target values. They are based on a variety of sources including EC (1995, 2004) and Herrmann et al. (2012). When reviewing the literature on radiography optimisation, there is considerable heterogeneity in the optimisation

solutions in various examinations (Steffensen et al., 2021). The exposure parameter set should be appropriate for the type of detector in the image receptor (Box 2.1). Combinations of tube potential and mAs should be established for different anatomical regions and possible patient characteristics, and exposure charts should be prepared for a full range of examinations for each x-ray unit. The level of image quality in terms of contrast and noise level required will depend on the clinical question to be answered. For example, the initial evaluation of a fracture without any displacement will require a high level of image quality, and perhaps additional image exposures, whereas for other orthopaedic applications where the contrast is high, a lower level of image quality will be adequate. The level of image quality can be defined as high, medium, or low according to the clinical task being undertaken, and the mAs chosen accordingly (EC, 2004; Busch and Faulkner, 2005; Uffmanna and Schaefer-Prokop, 2009). Exposures for some routine follow-up studies where the image quality required can be judged from previous images (e.g. for pneumonia or tube positioning) can be reduced substantially.

Box 2.2. Choice of the correct grid

A grid consists of a plate containing thin strips or lamella of lead lying perpendicular to the surface, sandwiched between layers of a low attenuation interspace material such as fibre or paper. X rays scattered at angles are attenuated by the lead strips.



Grids are categorised by the strip density in lines per cm and the grid ratio. Strip densities less than 45–60 lines per cm require mechanical movement to prevent the appearance of lines on the image due to aliasing. A typical value used for general radiography would be 40 lines per cm, and the grid would be mounted within a bucky that would provide the movement.

The grid ratio determines the effectiveness of the grid in removing scattered radiation, but also affects the transmission of the primary beam. The grid ratio depends on the modality and the source to image receptor distance. When there is less scatter, a lower grid ratio (8:1) with a lower tube potential will give the desired contrast level. Ratios of 10:1 or 12:1 are used commonly for table- or wall-mounted buckies, and 6:1 or 8:1 for imaging with mobile units. Grids can often be removed for paediatric patients or extremities, where there is less scatter. The strips may be parallel or angled so that the grid is focused towards the focal spot of the x-ray tube to improve transmission. The correct source to image receptor distance must be used to avoid cut-off of transmission at certain angles with focused grids.

(38) Scattered radiation reduces contrast in radiography, limiting the dynamic range of x-ray intensities that is available. Grids are employed to absorb the scattered radiation to improve contrast (Box 2.2), and are used for the majority of adult radiography examinations of the trunk or head, but are not required when imaging thicknesses of soft tissue less than approximately 12 cm, or for low attenuation examinations with low tube potentials (Table 2.1). Thus, grids are used for most adult radiography examinations, but may be dispensed with for examinations of small children. Modern digital radiography systems may also incorporate virtual grid algorithms where the effect of scatter is corrected computationally in the acquired images (see Section 2.3.3).

(39) Grid cassettes are used with mobile units in which the grids are lighter and easier to handle. As grids attenuate the transmitted x-ray beam and the specifications vary, exposure factors need to be adjusted upward to suit the arrangement. The regular lines in a grid can combine with the array of detector elements in the image receptor to produce an artefact with regular lines known as ‘aliasing’ caused by insufficient sampling.

(40) If a mixture of grid and non-grid exposures are carried out on the same unit, there should be a safety check before an image is taken to ensure that the unit is set up correctly. An agreed system, such as replacement of the grid after all non-grid exposures, can minimise the risk. Some equipment displays an icon to show if the grid is in place.

(41) In order to achieve a consistent exposure level, an AEC device is usually employed in fixed radiographic imaging facilities that terminate exposures at pre-determined levels (Section 2.2.2). AEC devices have settings that allow the exposure level to be decreased or increased, and these can be used to select lower or higher exposures for particular types of examination.

(42) Different values of tube potential may be selected depending on the imaging task; for example, a slightly lower tube potential may be used to visualise a rib fracture than that required for soft tissue imaging. Tube potential and mAs values need to be adjusted together, and fine-tuned when establishing exposure factors for use in a facility. Increasing tube potential without decreasing mAs will result in a higher dose to the patient, as output increases approximately as the square of the tube potential. If significant changes are to be made, assessments should be carried out on clinical image quality. Anthropomorphic phantoms, if available, can be useful for this, and criteria have been established for such assessments (EC, 1995, 2004)

Table 2.1. Exposure factors and expected dose levels for a range of imaging tasks.

Anatomy	Projection	kV	Grid	Additional filtration (mmCu)	ESAK* (mGy)	KAP* (Gy cm ²)
Chest	PA	120–140	Yes		0.05–0.2	0.06–0.1
Chest	PA	75–90	No		0.3–0.5	0.06–0.1
Lumbar spine	AP	75–90	Yes		2–6	0.7–1.5
Lumbar spine	Lateral	80–95	Yes		5–10	1.4–2.5
Abdomen	AP	75–90	Yes		2.5–5	1.4–2.5
Pelvis	AP	75–90	Yes		2–4	1.3–2.2
Newborn <5 kg	AP/PA	56–65	No	0.1–0.2	0.03–0.07	0.003–0.015
Infant 5–15 kg, chest (4 months–3 years)	AP/PA	60–80	No	0.1–0.2	0.04–0.08	0.005–0.022
Infant 5–15 kg, abdomen, pelvis (4 months–3 years)	AP	60–80	No	0.1–0.2	0.3–0.6	0.05–0.15
Child 15–30 kg, chest (4–10 years)	AP/PA	70–85	No	0.1–0.2	0.06–0.12	0.008–0.05
Child 15–30 kg, abdomen, pelvis (4–10 years)	AP	70–80	Yes	0.1–0.2	0.5–1.5	0.15–0.25

PA, postero-anterior; AP, antero-posterior; ESAK, entrance surface air kerma; KAP, kerma area product.

*Dose quantities represent a range of average values (first and third quartile values in a dose survey), and the adult values are for a 70-kg patient. If an indirect digital radiography system with caesium iodide is used, values should be towards the lower end of the range or lower. Doses from improved modern systems may go below the values listed.

(43) Metal filters are placed in x-ray beams to attenuate lower energy photons, few of which reach the image receptor (Box 2.3). These are incorporated as standard in medical x-ray tubes, and a minimum total filtration, which includes that inherent in the x-ray tube itself, is usually specified in regional/country regulations. For example, 2.9 mm of aluminium equivalent half-value layer (HVL) at 80 kV is required for x-ray tubes in the USA, whereas 2.5 mm of aluminium equivalent total filtration is the minimum requirement in the UK.

(44) Additional copper filters (0.1–0.3 mm) can give reductions of 20–50% in effective dose with tube potentials of 70–80 kV by removing more low energy photons, and are recommended routinely for paediatric examinations and for adults with caesium iodide digital radiography systems. However, adding excessive copper filtration can result in the reduction of image contrast with less differentiation between grey tones.

Box 2.3. Additional metal filters

Copper absorbs more lower energy photons in the 20–50-keV range than aluminium, and inclusion of a 0.2-mm-thick copper filter in radiographic units can reduce entrance surface air kerma (ESAK) and kerma-area product (KAP) by 50%. The reduction in effective dose for examinations of the trunk will be 40% with tube potentials of 70–80 kV, and 25% at 120–130 kV (Samei et al., 2005). The images below depict radiographs taken with and without copper filtration, and show minimal change in image quality but substantial reductions in KAP. Use of additional copper filtration has the advantage of lowering dose if the digital radiography unit is properly optimised, and it is recommended for units used for paediatric examinations (Section 5.2). It will also reduce ESAK and KAP for adult examinations, but copper filtration has the disadvantage that the mAs must be increased in order to maintain the same level of quantum noise. This may only be appropriate for higher sensitivity caesium iodide digital radiography systems (Box 2.1). The tube output at 80 kV would need to be increased by 15–20% for 0.1 mm of copper or 20–30% for 0.2 mm of copper, and this may have an impact on the x-ray tube lifetime and possibly lengthen exposure times.

If any additional filtration is incorporated into a system, the image quality and automatic exposure control settings should be evaluated thoroughly before the system is introduced into clinical practice to ensure that the diagnostic quality of the images is not compromised (EC, 2004).

Additional copper filters for clinical use are mounted in the tube housing before the KAP chamber. If a filter is placed after the KAP meter during initial trials to investigate the effect on images of a phantom, the KAP value will not record the dose reduction.

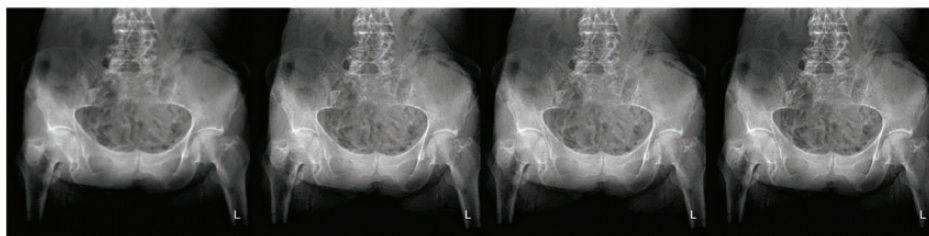


Fig. Pelvic radiographs taken at 81 kV with a Siemens Axiom Aristos FX showing the effect of additional copper filters. Exposures from left to right were taken with the following thicknesses of copper: 0 mm, 0.1 mm, 0.2 mm, and 0.3 mm. The relative values of kerma-area product for the four images are 1.0, 0.65, 0.4, and 0.3. (cadaver study). Source: Dean Pekarovic, University Medical Centre Ljubljana, Slovenia.

2.2.2. Automatic exposure control

(45) AEC devices are employed to control exposures and improve the consistency of image acquisition. An AEC device usually comprises a set of three x-ray sensors behind the patient that measure the radiation incident on the image receptor (behind any grid). The sensors are thin ionisation chambers, two to the upper right and left (over the lungs in chest radiography), and one usually lower down in the centre (over the spine). The number and position of the x-ray sensors may vary between x-ray units. Exposures are terminated when a pre-determined dose level is reached in order to ensure that consistent exposures are given to the image receptor for patients of different sizes. Use of an AEC device is recommended whenever possible, although small children may require manual techniques.

(46) AEC devices should be calibrated to suit the characteristics of the detector, and can be set up to maintain a constant EI value (see Section 2.2.3, Fig. 2.2). However, use of the SNR will provide a better option (Moore et al., 2014, 2016), and a practical method using this technique is described by Moore et al. (2019). The initial setting is crucial in determining exposure levels, and all chamber combinations should be tested regularly with phantoms representing a range of patient thicknesses [e.g. different numbers of sheets of polymethyl methacrylate (PMMA)] to ensure consistency.

(47) The variation in sensitivity of a digital detector with photon energy and thus tube potential depends on the phosphor material. While the sensitivity of caesium iodide digital radiography systems increases with tube potential, that for computed radiography systems declines, so the relative exposure needs to be increased slightly at higher tube potentials (Doyle and Martin, 2006). The EI for digital imaging systems relates to the level of image quality, and the relative response at different tube potentials follows a similar pattern to the SNR (Section 2.2.3). Therefore, maintaining a constant EI or SNR is recommended as the method of choice for setting up AEC devices for digital radiography.

(48) The noise level in the image and the SNR are determined by the image receptor sensitivity and the exposure level, and the AEC device should be used to achieve the desired level of image quality. AEC calibration curves are stored in the memories of x-ray generators to suit the energy dependence of different digital radiography systems, and the AEC device should be set up at installation of a new type of image receptor. AEC devices are usually set up relative to a pre-determined air kerma incident on the detector at 80 kV, and use different kV compensation curves so that the AEC device can be calibrated according to variations in detector sensitivity with tube potential. The initial setting of image receptor dose levels at 80 kV is crucial in determining the overall exposure level for radiographic imaging in a department. The images need to achieve the correct balance between image quality and dose, so involvement of all members of the core imaging team (radiographers, radiologists or other radiological medical practitioners, and medical physicists) is crucial.

(49) Considering exposure levels that would be required for different imaging tasks, high might correspond to an air kerma incident on the image receptor of 0.01–

0.02 mGy, medium to 0.002–0.005 mGy, and low to 0.001–0.002 mGy. The lower end of each air kerma range might correspond to that required for a digital radiography system, and the upper end to that required for a computed radiography system. The majority of AEC devices allow the exposure level to be decreased or increased in steps of 20–30%. These can potentially be used to adjust the exposures to give lower or higher levels for imaging tasks requiring different image quality levels.

(50) The AEC chambers selected will depend on the examination and the exposure level required in the region of interest. For example, the chamber behind the right lung would be selected for chest postero-anterior (PA) radiographs and the central chamber for spine examinations (EC, 1995). In modern units, the chambers used, together with exposure factors, will be pre-selected for different examinations. All combinations must be calibrated and thereafter tested regularly to ensure consistency between different chambers using a variety of tube potentials, and with phantoms representing a range of patient thicknesses (IPEM, 2010).

(51) A common mistake in the use of an AEC device is not centring the anatomical area of interest on the relevant chamber. There may be greater risks for certain examinations (e.g. lateral spine projections) when patients are lying on a table or trolley. A special group are paediatric patients, in whom there is a possibility that the AEC chamber and the anatomy may not overlap (Section 5.2). In cases when there is a significant risk of misaligning the anatomy and AEC chamber, use of the manual technique is recommended.

2.2.3. Exposure indicator

(52) Digital radiographic imaging systems can produce adequate image quality over a broad range of exposure levels, the only difference being in the noise levels. Images that have higher or lower noise levels than required are not readily recognisable at the time images are taken, so there is a risk of dose creep; dose increases of 40% have been reported (Gibson and Davidson, 2012). Exposure indicators have been developed by manufacturers of digital image detectors, and were later standardised following the recommendations of the American Association of Physicists in Medicine (AAPM) Task Group 116 (AAPM, 2009) and, more recently, AAPM Task Group 232 (Dave et al., 2018) and the International Electrotechnical Commission (IEC) (IEC, 2008).

(53) The detector exposure indicator is intended to reflect the exposure level at the image receptor within the relevant image area to facilitate the production of consistent, high-quality digital radiographic images. More specifically, the EI is related to the air kerma in μGy at the image receptor in the anatomical region of interest within the image, and so is a linear function of tube current. It should be noted that the EI depends on the body part selected, the body part thickness, the tube potential, the added filtration in the x-ray beam, and the type of detector, among other factors. As it is related to the air kerma incident on the image receptor, it provides a measure of signal acquisition, and thus, it is suitable for monitoring

change in imaging performance. The relevant region of the image for calculation of the EI is identified through segmentation of the relevant anatomical image area and the EI equated to the dose corresponding to the median of the distribution of pixel values within this area of interest (IEC, 2008; Dave et al., 2018). Comparisons can be made with an intended target value (EI_T) and a DI derived as:

$$DI = 10 \log_{10} \left(\frac{EI}{EI_T} \right)$$

(54) EI_T represents the optimal exposure for the particular body part being imaged, patient characteristics, and imaging task. EI_T should be determined by the optimisation team and will vary, to some extent, for different x-ray procedures performed, as it depends on the noise level required for the task. Default values of EI_T are set by the vendor, and these should be tested and adjusted for optimisation by the user for each anatomical region during the commissioning of new x-ray equipment. During clinical use, the DI should be used by radiographers to identify images that are under- or overexposed so that appropriate action can be taken. A DI of 0 indicates proper exposure, a DI greater than +1 indicates higher exposure than expected, and a DI less than -1 indicates lower exposure than expected (AAPM, 2009).

(55) It is important for radiographers and radiologists to understand how EIs can be used and their limitations. The EI is not a single measure of image quality as it is affected by many parameters, nor is it a patient dose indicator. The EI is a tool for quick assessment of the appropriateness of an exposure and monitoring exposure levels. The EI is included in the DICOM header of radiographic images and, together with dose (KAP), is useful for optimisation purposes (Fig. 2.2). The DI can be calculated and displayed on the interpreting workstation/PACS. By recording and monitoring exposure indicators and DI values, facilities can control dose creep. Analysing the percentage of images that fall outside an acceptable range can be used to educate radiographers, and decrease the variation while improving the image quality goals of the department.

(56) AAPM Task Group 232 recommends that a mean DI of 0.0 should be targeted for all body parts, and this requires care in setting appropriate values of EI_T in which vendors can aid the optimisation team (AAPM, 2018). The Task Group found that the DI could be characterised by a standard deviation (SD) which varied between 1.3 and 3.6 for the facilities assessed, and fewer than 50% of DI values fell within the significant action limit ($-1.0 \leq DI \leq 1.0$). They therefore recommended that action points for the DI should be set at ± 1 SD and ± 2 SD based on the actual data from the individual site, and data from the publication (AAPM, 2018) can be used as a starting point. If the collimators are wide open, this may affect the EI value assessed, giving a false indication of the exposure.

(57) It should be noted that the EI value can be quite dependent on the manufacturer. In addition, the definition has evolved with time, and older computed radiography systems from different manufacturers used completely different

definitions. The user needs to know how their system performs, and obtain calibration tables for the EI versus dose to detector or noise in a simple phantom, if there are uncertainties, or if different manufacturers cohabit in the same facility. Another point to note is that there are now AEC devices with five chambers, and these should be tested in an appropriate manner.

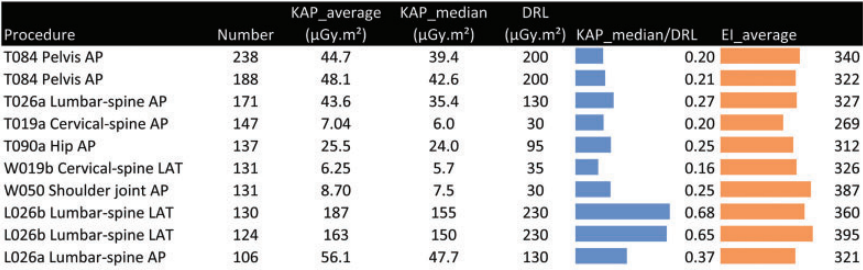


Fig. 2.2. Example of a spreadsheet chart used for monitoring kerma-area product (KAP) and exposure index (EI) values for selected radiographic examinations. The initial exposure index target value (EI_T) was set at 250, but could be modified by the user for each projection as exposure levels are established. Values for the deviation index could also be calculated and displayed. Reproduced with permission from: Urban Zdešar, University Medical Centre Ljubljana, Slovenia. AP, antero-posterior; DRL, diagnostic reference level.

2.3. Other aspects of optimisation

2.3.1. Source to image receptor distance and focal spot size

(58) The intensity of the x-ray beam is related to the SID by an inverse square law. In modern radiographic rooms, a fixed SID is normally used, with 100 cm being in widespread use, although some manufacturers recommend 110–115 cm, which will reduce the ESAK and detector dose by approximately 20% (Carroll, 2018), but this must be in concordance with the grid focus. Changing the beam geometry by extending the SID from 100 cm to 115 cm will improve spatial resolution (less blurring) and decrease magnification. For mobile radiography, the radiographer should adjust the mAs according to the inverse square law formula. As a rule of thumb, this involves increasing the exposure by 20% if the SID is lengthened by 10 cm, and reducing it by 20% if the SID is shortened by 10 cm.

(59) Increasing the SID can be used to reduce image magnification in order to include the complete anatomy within the image for large patients. The inverse square law should be used to achieve the same dose at the image receptor, although if the patient is large, it may be appropriate to increase the tube potential as well. However, the grid focal distance should be considered in determining the correct SID, and any changes to the SID should be made in collaboration with the medical physicist.

(60) X-ray tubes are typically provided with two focal spot sizes linked to the apparent size of the imaging source that is related to the tube filament size. The small

focal spot should be used for clinical indications where visualisation of subtle anatomical detail is required, when the tube loading allows – such as with small body parts in musculoskeletal digital radiography, and if the prolonged exposure time is acceptable regarding patient motion. Some reports suggest that differences between small and large focus are not always visible in digital radiography, but experienced radiologists may observe more blurred details when a large focus is used and the image is viewed on a diagnostic display.

2.3.2. Field of view and collimation

(61) Essential to the training of every radiographer and others operating x-ray equipment is the importance of collimating the x-ray beam to the anatomy to be imaged. This is facilitated for computed radiography by the wide range of cassettes available, which encourages radiographers to consider image size, but digital radiography image receptors are usually only available in two plate sizes [43 cm × 35 (or 43) cm and 24 cm × 30 cm] and this can encourage poor practice. Recently, more digital radiography receptor options, such as neonatal chest receptors, have been offered but they are expensive. Radiographers have a simple tool available to crop digital radiography images, and it is easier in practice to use a larger FOV and crop the images. Using a larger FOV than necessary will not only result in unnecessary exposure of more tissues surrounding the area being imaged (and give a higher KAP), but will also produce more scatter from the surrounding tissues and thus degrade the image quality (Shields and Bushong, 2012). Poor collimation in images of neonates is prevalent in some centres, and can lead to unnecessary exposure of adjacent tissues, as shown in Fig. 2.3a,b.

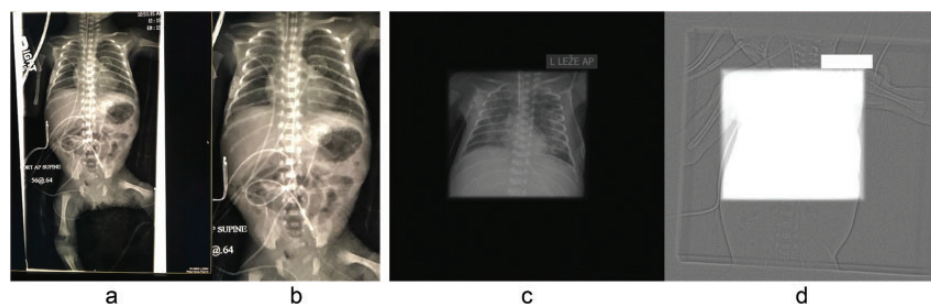


Fig. 2.3. Issues in image collimation in two cases. (a) and (b) show a portable babygram in a neonatal intensive care unit to determine umbilical vein catheter placement position: (a) original image which is poorly collimated, and (b) image with the appropriate collimation. Source: Kimberly Applegate, Department of Radiology, University of Kentucky, USA (retired). (c) and (d) show the use of windowing to identify very poor practice in cropping an image: (c) a cropped image as seen on screen, and (d) with adjusted windowing to show the real collimation of the actual radiograph as exposed. Images of this type can be used for auditing poor collimation practice where this is an issue. Source: Dean Pekarovic, University Medical Centre Ljubljana, Slovenia.

(62) The central importance of collimation for patient dose (and KAP values) and image quality cannot be overemphasised throughout the training of radiographers and others operating x-ray equipment. Suboptimal practice should be identified through regular audit of KAPs against expected values. In departments where collimation practice is suboptimal, examples of good versus poor collimation digital radiography and a table showing how larger FOVs affect KAP could be displayed. Radiographers should be aware that poor practice can be identified during audits through differences in KAP values and adjustments of windowing in computed radiography to show the original exposed FOV for non-collimated images (Fig 2.3c,d).

2.3.3. Virtual grids

(63) Some vendors offer ‘virtual grid’ software, sometimes called ‘gridless’ or ‘scatter correction’ software, which incorporate algorithms to remove the contrast-reducing low frequency effect of scatter in the acquired images (Mentrup et al., 2014). The scattered photons still reach the image receptor, and contribute to the quantum noise, which manufacturers often reduce through pixel averaging. Some algorithms are based on Monte Carlo simulations of the passage of x rays through water, and a calibrated correction step that is tailored to mimic the properties of an anti-scatter grid. A grid-adapted scatter image is then subtracted from the original detector image to reduce scatter content. However, virtual grid algorithms vary significantly between vendors, and some are only simple post-processing operations. Therefore, the application of virtual grids should be considered separately for each examination type and equipment model. Virtual grids may enable more extensive radiographic imaging without grids, and help to maintain sufficient image quality as regards to scatter (e.g. in mobile chest x-ray imaging). Examples of chest images before and after application of a virtual grid are shown in Fig. 2.4, and images obtained with a standard and a virtual grid are compared in Fig. 2.5.

(64) Virtual grid software can be useful in situations where there are practical difficulties in taking a radiograph, and the lower quality of the image obtained is still acceptable. This may be when the patient cannot cooperate for positioning, is on a trolley or bed, or in the case of trauma, either in the radiology department or with mobile units. Virtual grid software will allow lower exposure factors to be used, although this should not be a reason for not using a physical grid where one is required. If a grid is removed from a bucky for any reason, a check must be carried out afterwards to ensure that it is replaced and in the correct orientation before a new patient is imaged.

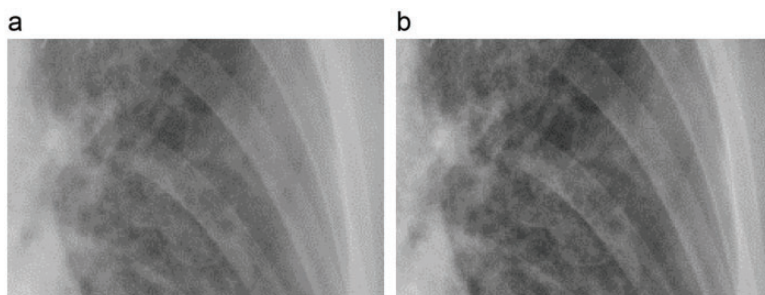


Fig. 2.4. Chest images (a) before and (b) after application of virtual grid software, demonstrating improved image quality in (b) (Philips Skyflow). Reproduced with permission from: Koninklijke Philips N.V.

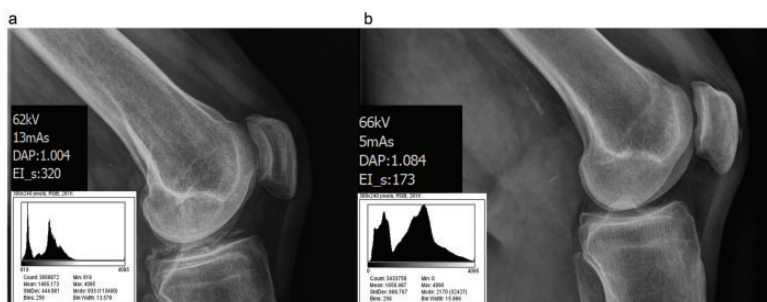


Fig. 2.5. Comparison of images of two patient knees obtained (a) with an actual grid and (b) with virtual grid software (Philips Skyflow). Both radiographs show high image quality. Source: Dean Pekarovic, University Medical Centre Ljubljana, Slovenia. DAP, dose-area product; EI, exposure index.

2.3.4. Patient protective equipment (shielding devices)

(65) The use of patient gonadal shielding during x-ray-based diagnostic imaging should be discontinued as routine practice. The reason for this is that it provides little benefit to patients' health, exposures per digital radiography examination have declined, and shielding can have a negative effect on the efficacy of the examination (AAPM, 2019c; Hiles et al., 2021). Moreover, there is no evidence of human heritable effects resulting from exposure of the gonads (ICRP, 2007b). However, ICRP Task Group 121 will review the recent literature on radiation risk to the offspring and future generations. Patient shielding is ineffective in reducing internal scatter, which is the main source of radiation dose to internal organs that are outside the imaging FOV (Marsh and Silosky, 2019; Hiles et al., 2020, 2021; NCRP, 2021). The shielding may obscure pathology, introduce artefacts that will degrade image quality and image processing in digital radiography, or interfere with the exposure of an

AEC chamber, thereby increasing the dose. Contact shielding is not recommended, and the effectiveness of shielding outside the FOV is minimal. More efficient optimisation methods on modern digital imaging equipment with specific dose reduction options and conventional dose management features can be implemented, including attention to close collimation.

(66) Patients or carers may expect gonadal shielding to be used, as it has been a rule of good practice for many decades. Changing the practice will take time, requiring stakeholder education, and raising awareness of professionals such as radiological medical practitioners and radiographers, as well as awareness of carers, patients, and families.

(67) During training, radiographers must be aware that as well as gonadal shielding, anything which is not part of the requested anatomy must be removed when possible, or at least moved out of the FOV, especially when there is a risk of it lying over an AEC chamber. Objects that could affect the image, such as belts, jewellery, trusses, or other supporting garments, should be removed, but this also includes limbs which, if positioned incorrectly, may overlie important anatomy (Image Wisely, 2022c). For chest x rays with lateral projections and elderly patients needing to use the support bar when standing, the position of the arms should be checked. If arms are flexed too much at the elbows, they can affect image quality and AEC chamber performance.

Table 2.2. Recommendations for patient shielding in diagnostic radiology (Hiles et al., 2020, 2021).

Scenario	Recommendation	Comments
Patient contact shielding for protection of breast	Not recommended	Use PA positioning rather than shielding for spinal and chest examinations where possible. If using AP projection, a scoliosis shawl may be considered.
Patient contact shielding for protection of thyroid	Not generally recommended	May be used for paediatric patients in cephalometric radiography if evaluation of the cervical spine is not needed or the spine is not obscured. The effectiveness of shielding outside the FOV is minimal, and potential interference of the shield with the AEC must be avoided.
Patient contact shielding for protection of gonads	Not recommended	Male adult and paediatric patients: may be considered where gonads are <5 cm from the primary beam. Female adult and paediatric patients: not recommended for imaging in the pelvic region.
Patient contact shielding for protection of lens of the eye	Not recommended	Use PA skull positioning, no recommendations for shielding.
Pregnant patients	Not recommended	For examinations within pelvic region (from diaphragm to knee), consider non-ionising imaging alternatives. If ionising radiation must be used, carry out a thorough justification and risk assessment process.

PA, postero-anterior; AP, antero-posterior; FOV, field of view; AEC, automatic exposure control.

2.3.5. Reject and retake analysis

(68) A reject and retake analysis programme should be in place to allow radiographers to learn when images are suboptimal or non-diagnostic. This tool is often undervalued in an optimisation dose tracking programme. The move to digital radiography should have decreased the number of repeat radiographs in theory, because of the wide exposure latitude. However, this has not been the case, as image acquisition is easier and facilitates the ease of taking repeats. The analysis of rejected and repeated images in digital radiography is complex and time consuming (AAPM, 2015; Jones et al., 2015). There may no longer be physical evidence of rejected images, and on early systems, operators simply deleted unwanted images with no record being made. This may be considered to be unethical practice. Even if this is not the case, rejected images may simply reside in the system until they are removed to free-up space.

(69) Reject and retake analysis should be included as part of the QA programme, and enacted through the quality management system (ICRP, 2023). Data should be collected and analysed regularly; monthly may be appropriate for a medium to large department. Reject and retake rates should be calculated and documented by body part and facility location, and education/training or corrective action should be taken if specific rejected image rates are above a pre-determined threshold (or national benchmark) or start to rise. Rejects and retakes should be reviewed as a collaborative task between the radiologists/radiological medical practitioners and radiographers, with the reasons highlighted, as this can be a powerful self-assessment tool to enable and encourage improvement in practice. Guidance on data reporting and workflows to enable an effective reject rate monitoring programme has been provided by AAPM (2023).

2.4. Factors to consider in optimisation

(70) The various factors, termed ‘actions’, that can influence digital radiography dose and image quality, many of which have been mentioned already, are brought together in Table 2.3. These actions which can increase or decrease patient dose are based on Table 2.3 in *Publication 93* (ICRP, 2004), but have been extended to include a wider range of actions.

Table 2.3. Actions that can affect patient dose and image quality.

Action	Effect on dose	Influence on image quality or diagnostic information
Increase mAs to reduce quantum noise	Increase	Improvement in SNR
Increase mAs further to give a significant reduction of noise (with detector saturation in some areas)	Increase	Deterioration, retakes
Use appropriate tube potential and establish correct radiographic techniques for digital systems	Decrease	May change appearance of image (optimisation)
Increase kV and reduce mAs to maintain same noise level	Decrease	Decrease in contrast (process of optimisation)
Inclusion of 0.1-mm or 0.2-mm copper filter in beam with increased mAs to maintain noise level	Decrease	Minimal effect, possible increase in exposure time
Implementation of dose and image quality indicators (KAP, EI, DI) on the console of x-ray system or PACS	Decrease	Potential improvement, potential decrease in retakes
Reduction in number of images per procedure (e.g. avoiding lumbosacral spine image)	Decrease	Unchanged or reduction in diagnostic information
Increase source to detector distance	Decrease	Reduced geometric unsharpness
Increase in size of x-ray tube focus	Unchanged	Reduced spatial resolution, decrease in exposure time and temporal resolution
Decrease in size of x-ray tube focus	Unchanged	Improved spatial resolution. May increase exposure time and decrease temporal resolution
Expose full digital radiography image plate and electronically crop image to required anatomy (poor practice) (proper collimation should use the light beam and anatomical landmarks)	Increase	Loss of contrast due to scatter from other tissues
AEC system not set up for correct image receptor type or calibration incorrect	Increase or decrease	Potential degradation
AEC system not used	Increase or decrease	Degradation, retakes
AEC chambers not checked regularly	Increase or decrease	Degradation, retakes
Incorrect positioning of patient, centring of x-ray beam, and consideration of AEC chamber position	Increase	Potential degradation
Use of computed radiography storage-phosphor plates beyond the recommended lifetime	Increase	Loss of quality, retakes
Use of a grid with too high a grid ratio	Increase	Susceptibility to grid misalignment faults
Use of focused grid at a different focus to image distance	Increase	Loss of information and quality in parts of image
Use of a grid with too low a line density	Possible decrease	Risk of aliasing artefacts

(continued on next page)

Table 2.3. (*continued*)

Action	Effect on dose	Influence on image quality or diagnostic information
Use of virtual grid software	Reduce	Poorer image quality than using a grid
Deletion of image files at the viewing station or workstation of apparently non-useful images	Possible increase	Loss of information that might be useful in reject/retake analysis
Poorly adjusted/optimised diagnostic monitor (e.g. insufficient brightness, contrast, or resolution)	Possible increase	Loss of information, potential for repeats
Use of workstation with more facilities to visualise images (window, level, inversion, magnification)	Potential decrease	Obtain more information from the same image and decrease in no. of repeats
Implementation of reject and retake analysis programme	Decrease	Possible improvement
Problems in postprocessing: hardware, network, etc. during archiving of images	Increase	Occasional loss of images or retakes
Loss of images in the network or PACS due to improper identification or other reasons	Increase	Retakes
Use of incorrect post-processing introducing false lesions or pathologies due to artefacts	Possible increase	Loss of information and need for retakes, potential misdiagnosis
Availability of workstation for post-processing (and for radiographers) to avoid some retakes	Decrease	Improvement
Allowing easy access to the PACS and teleradiology to look at previous images	Decrease	Improvement
Use of alternative post-processing option, which can sometimes avoid repetitions	Decrease	Improvement
Inability to post-process images stored in the PACS, so that re-analysis of images is not possible	Potential increase	Potential need for retakes

SNR, signal-to-noise ratio; KAP, kerma-area product; EI, exposure index; DI, deviation index; AEC, automatic exposure control, PACS, picture archiving and communication system.

2.5. Image post-processing

(71) Computed radiography workflow can be divided into exposure of the computed radiography plate, the read-out process in the computed radiography reader, and erasure of the plate. The readout process has several components, exposure field recognition, histogram analysis, and greyscale rendition (Fig. 2.6) (Seeram, 2019). For digital radiography, the image data are recorded at the time of exposure, eliminating the readout step.

(72) Manufacturers have proprietary post-processing algorithms that include contrast enhancement, spatial frequency or edge enhancement, and multi-frequency

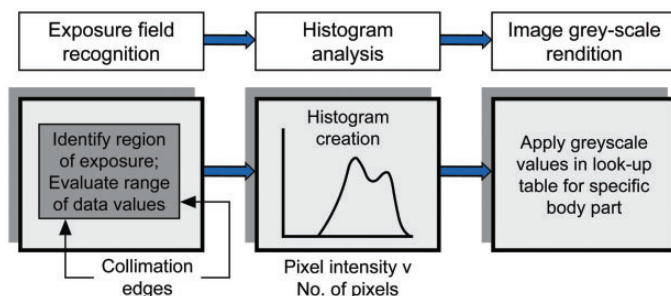


Fig. 2.6. The basic steps in processing of digital x-ray images. Source: Colin Martin, University of Glasgow, UK.

enhancement in which different spatial frequencies are manipulated separately. Computed radiography systems have numerous pre-installed look-up tables linking grey levels to exposure for different anatomical regions (e.g. head, chest, etc.). The appropriate look-up table must be selected before the image is delivered to the PACS for reading, and use of an inappropriate selection may lead to a poor-quality image that has little value for diagnostic purposes.

(73) Windowing is a key tool used for adjusting image visualisation (Seeram, 2019). The window width is the width of the range of pixel intensities displayed in the image, and the window level is the mid-point of the range. The appearance of a digital radiography image can be improved (or, more often, altered temporarily by the viewer while reviewing the images for interpretation) through adjustments of greyscale, and use of window width/window level can be used to achieve better diagnostic image quality in parts of the image with varying contrast (Fig. 2.7).

(74) Before an image is archived, contrast and edge enhancement can be adjusted to achieve better visibility of the required anatomy or pathology. Although these

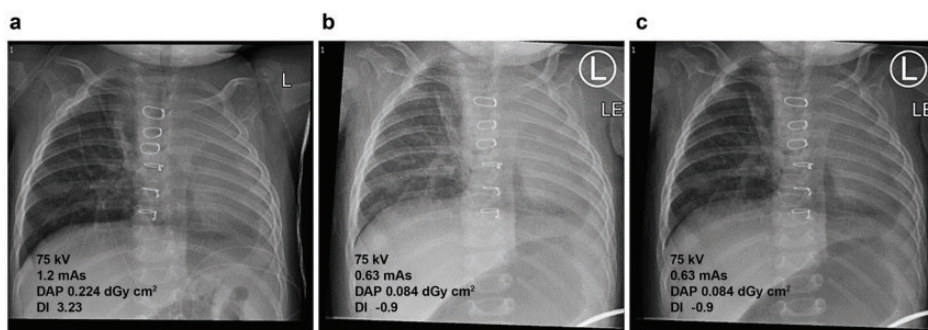


Fig. 2.7. Windowing adjustment example. Paediatric chest images recorded at 75 kV in a Neonatal Intensive Care Unit: (a) with 1.2 mAs, KAP 0.0224 Gy cm², DI 3.23, and b) and c) with 0.63 mAs, KAP 0.0084 Gy cm², DI -0.9. Windowing has been used in c) to improve the contrast of the lower dose image.

tools can improve an image, they do not replace appropriate choice of the exposure parameters and well-adjusted indication-specific post-processing.

(75) Before setting up protocols, it is important for the user to become familiar with image post-processing steps, and how different algorithms, which are often vendor specific, affect image quality. During the initial protocol implementation phase, the imaging of anthropomorphic phantoms can help in fine tuning the post-processing tools prior to introduction into clinical use. Radiographers, radiologists, and medical physicists should work together to identify the most appropriate processing algorithms for reporting when a new radiography system is commissioned. During protocol creation, different options for post-processing should be investigated on clinical images when time is available on the PACS for image review. This will aid selection of the most appropriate look-up table, and can help to identify lower dose options that will give a similar quality image or obtain improved image quality for the same dose. Fig. 2.8 shows the same patient with the same exposure parameters, and illustrates the effect of different post-processing algorithms. Optimised practices and imaging protocols should be harmonised throughout an organisation with many devices.

(76) There are pitfalls in overapplication of post-processing which can highlight features in the image that are not significant clinically. For example, if multi-frequency post-processing is carried out on chest x rays for patients in the supine position on a trauma mattress, the folds of the mattress may be enhanced and appear in the images suggesting an abnormality.

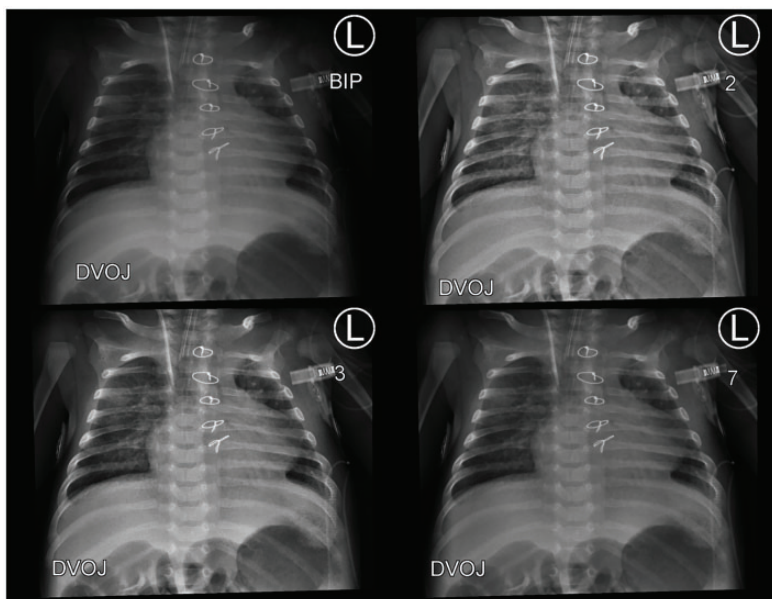


Fig. 2.8. Chest radiographs of the same patient with similar exposure parameters, on which different post-processing algorithms and look-up tables have been used. Source: Dean Pekarovic, University Medical Centre Ljubljana, Slovenia.

2.6. Optimisation of the imaging workflow

(77) When changing technology in the clinical environment, all team members should be made aware what changes mean for the daily workflow, and how to control image quality and dose. The Ten Steps to Help Manage Radiation Dose in Paediatric Digital Radiography published by Image Gently provide a good starting point for auditing radiography performance, planning, and allocating the who, how, and when for each step (Image Gently, 2022a). The roles and responsibilities for all team members should be defined clearly to enable them to work together to achieve the objective. The basic steps are discussed in detail in Section 5.2.1.

(78) A digital radiography safety checklist is recommended by Image Gently, divided into four steps including what should be considered in each step (Box 2.4) (Image Gently, 2022b). The checklist is intended as a QA and improvement tool to assist radiographers that perform portable digital radiography, and to reinforce the safety practices.

Box 2.4. Safety steps to image and verify for your patient (adapted from Image Gently)

Prior to starting the examination

1. Patient name selected from the worklist
2. Patient properly identified (at least two-point verification: name, surname, date of birth, name of relative/parent, also address can be considered)
3. Appropriateness of request checked
4. Explained the examination to patient/parent
5. Verified last menstrual period/pregnancy status if appropriate

Image capture during the examination

1. Beam, body part and image receptor aligned, source to image receptor distance checked, use of grid determined
2. Patient positioned and body part measured, cassette positioned (computed radiography alone)
3. Beam collimated
4. Technical factors selected
5. Proper positioning, placement of markers, and immobilisation
6. Final adjustment of tube and settings made
7. Breathing instructions given
8. Exposure taken

Image critique immediately after exposure

1. Cassette transported to and processed in reader (computed radiography alone)
2. Images displayed and reviewed; identification confirmed

3. Image quality reviewed
4. Exposure indicator/index checked; deviation index compared with target exposure index
5. Image reprocessed or repeated as necessary

Following completion of the examination

1. Post-processing performed if necessary
2. Examination verified and images archived to picture archiving and communication system for reporting

2.7. Basic quality assurance

(79) Acceptance testing and commissioning are crucial to ensure that equipment is performing optimally. Before any imaging system is first used, an acceptance test should be performed to verify image quality, dose, and compliance with the manufacturer's specifications (ICRP, 2023). After commissioning, medical physicists and radiographers should work together to establish a local QA and management programme involving QC and other tests on different components of the system, with defined tolerances and frequencies for all tests performed (IPEM, 2010; AAPM, 2006, 2015; IAEA, 2023b).

2.7.1. Computed radiography systems

(80) The acceptance test for a computed radiography reader and cassettes should identify any areas of knowledge about which staff are uncertain, and dedicated training given to radiographers about parameters used. Detailed QC testing is necessary to monitor the system performance, together with defined tolerances and frequencies for all tests performed (AAPM, 2006; Walsh et al., 2008; IPEM, 2010). Computed radiography plates and the computed radiography reader in every x-ray room should be checked, with a system of daily reporting of any differences in the imaging chain, which should be investigated immediately. Computed radiography plates that have not been in use for >24 h should be erased before use. There are two types of erasing: the fast erase is used on a daily basis, but a deep erase on all plates is recommended periodically.

(81) Any cassette that has not been used for some time should be cleaned with a dedicated cleaning fluid before being inserted into the computed radiography reader. Too frequent and inappropriate cleaning of the screens can discolour the phosphor and create artefacts on the images. Computed radiography plates are not waterproof, and inappropriate cleaning of the cassette housing after use with a fluid can lead to permanent damage to the phosphor plate.

(82) Computed radiography plates can be damaged during the readout process by dust or particles of wet plaster (from patient casts). When artefacts on computed radiography plates are recorded during QC tests, it is not necessary to withdraw the

computed radiography plate from use. If they are near the edge and should not jeopardise the diagnostic quality of the image, it is sufficient to inform radiographers of the exact position of the artefact and keep a record, identifying the affected plates. A QC radiographer might dedicate a plate for use for pelvic or abdominal imaging alone, and instruct other radiographers to avoid paediatric or adult chest imaging where artefacts will be more visible. This can extend the lifetime of a computed radiography plate, which can be important if funds are limited.

(83) The EI for computed radiography plates is linked to the SNR performance, and this will deteriorate gradually over time, so cassettes need to be replaced. If a department has cassettes with a range in age or use, there is likely to be a range in EI values, which will be apparent when the EI is monitored. When new computed radiography plates are introduced, they should be put through a quick and simple acceptance test to inspect and check the plate quality.

(84) QC is achieved through exposures of test objects or phantoms, usually containing simple patterns, to assess the whole imaging chain (EC, 2004; ICRP, 2023). Some manufacturers provide dedicated QC software with phantoms, and the phantoms, measuring devices, and automated QC software should be requested at purchase. QC software can enable assessments to be carried out in shorter times, and record images and tables of data automatically.

2.7.2. Digital radiography systems

(85) Performance measurements for digital radiography image receptors are similar to those for computed radiography plates. A simple QC test prepared in collaboration with medical physicists can be performed daily and according to a pre-installed QC protocol. Simple QC tests and established baseline values can provide an effective tool for system inspection on a daily basis, checking and controlling the performance of different components of the system, such as AEC performance, tube output, and detector homogeneity (AAPM, 2006). Daily QC tests are quick, and enable radiographers to become familiar with baseline values.

2.8. Approaches to optimisation

(86) Digital radiography offers more flexibility in exposure level, giving the potential for images to be obtained with lower exposures, and enabling levels to be adapted to the diagnostic requirements of particular examinations. However, this capability is often not considered and standard exposure levels are widely used. Radiology facilities should therefore implement continual development of protocols and harmonisation across all the departments or facilities within the organisation in order to achieve higher levels of optimisation. Box 2.5 sets out some of the arrangements that might be expected to be in place for x-ray facilities at different levels. Level D facilities, that have not yet achieved basic optimisation, should aim to put in place the arrangements under Level C as the first step.

Box 2.5. Arrangements that should be in place for facilities at different levels of optimisation, together with aims that would be pursued

C: Basic

- Established protocols with appropriate tube potential and mAs settings for all common examinations
- Perform regular quality control/quality assurance tests on all digital x-ray units and computed radiography readers
- Radiographers have received comprehensive training and receive further update training whenever new units or features are implemented

B: Intermediate

- Radiographers have access to diagnostic quality workstations to verify image quality and settings
- Full range of protocols established based on specific clinical indications
- Image quality/exposure levels in protocols identified as low, medium, or high based on clinical indication
- Exposure index values recommended for a wide range of examinations and monitored regularly
- Continual development of protocols through regular radiographer/radiologist/medical physicist communication
- A quality management system is implemented to maintain performance levels
- Reject and repeat analysis programme implemented

A: Advanced

- Unified guidelines for clinical-indication-specific examination protocols throughout organisation
- Utilisation of a dose management system for organisation-wide online monitoring of patient exposures and analysis of exposure parameters for optimisation
- Standard, objective, and ongoing processes for evaluating optimisation undertaken with defined timelines
- Development of objective and quantitative image quality metrics based on diagnostic image quality criteria (e.g. by model observer or comparable method). Establishment of more comprehensive and consistent optimisation based on these criteria
- Use of anthropomorphic phantoms in optimisation
- Use of a generic approach, whereby the optimisation of exposure and post-processing parameters, and related exposure index values could be included in the commissioning of new equipment

3. INTERVENTIONAL AND OTHER FLUOROSCOPIC PROCEDURES

(87) Key points in this section:

- Fluoroscopy is an interactive imaging procedure requiring proper use of equipment features to perform the clinical task with the lowest possible radiation dose to the patient and staff members.
- Optimisation requires appropriate selection and configuration of a complex set of design features for the fluoroscopy system, tailored to the clinical tasks and required level of image quality.
- Optimisation should consider radiation risk in conjunction with other non-radiation-related risks (e.g. use of contrast media, medications, sedation/anaesthesia, etc.). The proper timing of a procedure and its optimal performance should be balanced carefully for individual patients and each clinical situation.
- Protocols should be configured to give the required image quality and dose saving needs for the clinical task. This includes the settings for the automatic dose rate control (ADRC) system and other programmes for which acquisition parameters are changing.
- QC programmes should be established to evaluate performance of all exposure modes relating to selection of options that are optimal for specific imaging tasks.
- X-ray beam projection and angulation with C-arm systems should be selected to provide the required anatomical visualisation, bearing in mind that steep angulations increase patient dose.
- For complex interventional procedures, where there is a risk of skin injury, cumulated dose quantities should be monitored during the procedure and recorded on completion. Appropriate trigger levels should be pre-defined for patient follow-up and management of tissue reactions. Exposure from previous and potential future procedures should also be considered.
- The use of low fluoroscopic pulse rates and pulse lengths, proper collimation, and changing the angulation and beam entry to reduce the possibility of overlap of radiation fields from different projections should be used to keep peak skin dose (PSD) below the threshold for skin injury.
- Components of the QA programme dealing with dose management should be put in place to enable the optimisation process to progress, and a core team should be established to promote optimisation through review of common fluoroscopic procedures.

3.1. The evolution of fluoroscopic techniques

(88) Fluoroscopy produces dynamic images of structures and organs in real time, which allow for its application for diagnosis and for navigation of instruments to perform different surgical, minimally invasive, and interventional procedures.

(89) This section deals with optimisation of all aspects of the use of fluoroscopy, including interventional radiology and cardiology. It covers fluoroscopy performed in the radiology department or other dedicated facilities, as well as use of mobile fluoroscopy in operating theatres and hybrid rooms, and the application of cone beam CT incorporated into fluoroscopy equipment.

(90) Since its discovery, significant advancements have been made in fluoroscopy equipment and techniques, which have impacted their clinical use. Since the invention of the x-ray image intensifier (II) and the television camera in the 1950s, improvements in intensifier technology and image displays, in parallel with developments in x-ray tubes and generators, have enabled enhancement of image quality while allowing the radiation doses to patients to be reduced substantially. This trend has continued with the introduction, in 2000, of digital systems based on flat panel (FP) detectors which are currently widely available and continue to develop (Balter, 2019).

(91) Fluoroscopy was initially a technique used only by radiologists in diagnosis, but this changed with the development of fluoroscopically guided percutaneous procedures, and is now in widescale use as the method of choice for complex interventions by many different medical specialists (UNSCEAR, 2008, 2022). While the frequency of diagnostic fluoroscopy studies (e.g. barium meal and urologic studies) has decreased, many being replaced by cross-sectional imaging [ultrasound, CT, magnetic resonance imaging (MRI)] and minimally invasive alternatives (endoscopy), fluoroscopically guided interventional (FGI) procedures have increased in type, number, and complexity. The estimated annual total of approximately 24 million interventional radiology procedures in the latest UNSCEAR report represents a six-fold increase from the 3.6 million procedures in the earlier report, while the collective dose has risen by a factor of 8. The increased use is due to the relatively low invasiveness and risk, faster recovery times, shorter hospital stays, and lower cost of FGI procedures compared with surgery.

(92) However, FGI procedures are performed in a variety of settings, and sometimes by clinicians with insufficient knowledge and awareness of radiation exposure. This puts patients and staff members at increased risk, not only for long-term stochastic effects, but also for tissue reactions such as skin injuries and cataract (ICRP, 2000b, 2010, 2013a; IAEA, 2010). It is critical that all radiological medical practitioners receive appropriate education and practical training before undertaking any FGI procedures. The optimisation task in fluoroscopic imaging is far from trivial. It should start with the establishment of a core team of a radiologist or other radiological medical practitioner, radiographer, and medical physicist properly trained in fluoroscopic techniques. When FGI procedures involve other clinicians, surgeons, nurses, and anaesthetists, they must understand the radiological protection principles of justification and optimisation, and undergo both initial education and ongoing training in radiological protection of their patients and themselves (ICRP, 2009, 2018b, 2023; NCRP, 2010).

(93) Fluoroscopy is an interactive imaging procedure requiring proper use of equipment features to perform the clinical task with the lowest possible radiation dose to the patient and staff members. Optimisation requires appropriate selection and configuration of a complex set of design features for the fluoroscopy system, tailored to the clinical tasks and required level of image quality.

(94) Optimisation in fluoroscopy comprises several equally important steps, which should be appreciated and implemented in practice. These are:

- Appointing a multi-disciplinary team (medical physicist, radiographer, and radiologist or other radiological medical practitioner) to establish appropriate design features for selection of a fluoroscopy system consistent with the intended clinical uses (Section 3.2).
- Proper configuration and exposure setting optimisation at the time of commissioning of the system, tailored to the clinical tasks and required image quality (Section 3.3).
- Establishment of a QA programme by the facility management along with the core team to establish and promote optimisation through reviews of common fluoroscopic procedures (Section 3.8). The programme should include equipment maintenance and QC tests to verify the equipment performance (Sections 3.4, 3.5, and 3.7).
- Setting up a dose management system applied to facilitate regular or continual patient dose monitoring and audit.
- Appropriate use of the available equipment features and settings by the operators to perform the clinical task with minimum possible exposure to the patient and the clinical team members (Sections 3.6 and 3.7).

3.2. Design features of modern fluoroscopy systems relevant to patient dose and image quality

3.2.1. Major equipment components

(95) Fluoroscopy systems are manufactured in a variety of configurations, allowing optimisation of the system for the intended clinical tasks. The main configurations are: (i) conventional fluoroscopy systems with the additional capability to perform radiography; (ii) C-arm systems; and (iii) angiography systems (see Box 3.1 for further details). Appropriate selection of the design features of a fluoroscopy system consistent with the intended clinical uses is imperative if the dose management QA programme is to function as intended.

(96) A fluoroscopy imaging system generally includes a high-power generator, a high heat capacity x-ray tube, and an image receptor, which could be either an II or an FP detector. It also commonly includes filters (Box 2.3), a field restriction device (collimator) attached to the tube housing, and an anti-scatter grid attached to the entrance surface of the image receptor, the role of which is to remove the scatter radiation and improve image contrast (at the price of increased dose) (Box 2.2). The anti-scatter grid should be easily removable, especially when the system is to be used for paediatric patients.

(97) Image receptors for both IIs and FP detectors are available in a range of sizes, varying from approximately 10–15 cm up to 40 cm in size depending on the intended clinical application. Complementary metal-oxide semiconductor detector technology provides superior image quality, compared with more traditional a-Si:H-based detectors, in both fluoroscopy and cone beam CT scan modes in modern C-arms, especially regarding low-dose and high-resolution conditions (Sheth et al., 2018).

(98) Fluoroscopy equipment can be operated in either fluoroscopy or radiography mode. Most applications involve the use of both modes to combine the good temporal resolution of fluoroscopy with the higher SNR and recording/archiving capabilities of radiography. In fluoroscopy mode, the images are viewed in real time but not always recorded. In the radiography mode (also called ‘fluorography’ in older systems), the images are recorded as single (spot) images, a number of images (acquisition), or as a sequence of serial images (also called ‘cine’) that can be viewed after the procedure. Patient doses per image frame in radiography mode can be orders of magnitude higher than those in fluoroscopy mode.

(99) Fluoroscopy/radiography mode is selected on the console, or by the operator at the start of or during the study, and is based on the intended application or clinical question using protocols defined within the equipment. The tube current in radiography mode is tens to a hundred times higher than in fluoroscopy to provide high SNR in a short exposure time. Operators need to be aware of the difference between the modes, including the associated dose rate. The use of radiography for recording/archiving and the number of recorded images need to be limited to the minimum necessary for the clinical task.

Box 3.1. Types of fluoroscopy equipment

Conventional radiography/fluoroscopy systems combine fluoroscopy and radiography. These systems have been used for a wide variety of diagnostic fluoroscopy examinations such as barium contrast studies of the upper and lower gastrointestinal tract, although many of these examinations have now been superseded by other non-fluoroscopic techniques. The systems are also used for contrast injections of the urinary tract, vascular and other catheter devices, percutaneous drains, and therapeutic interventions that involve the gastrointestinal, gastrourinary, chest, musculoskeletal, and vascular systems. Equipment consists of a patient table that can be tilted from a horizontal to a vertical position to distribute the contrast through the organs or structures of interest. The system most often has an x-ray tube fixed under the table, and a large field-of-view (FOV) image receptor above the table, which can be moved by the operator closer to or further from the patient. A variation of the combined radiography/fluoroscopy system is the remote-control radiography/fluoroscopy system, which features the opposite configuration with the x-ray tube above the table, and the image receptor fixed under the table.

‘C-arm’ geometry systems are either fixed or mobile, and allow for an easy change of the projection angle adapted to the clinical needs. This configuration enables alignment of the central radiation beam with the centre of the radiation

detector, regardless of the displacements that are performed during the clinical procedures. Mobile systems are often used in theatres to be positioned next to the operating table, and images are used to navigate a variety of treatment procedures, including minimally invasive procedures in orthopaedic surgery, traumatology, general surgery, urology, gastroenterology, pacemaker and vascular access placement, etc. The C-arm systems have an x-ray tube at a fixed distance from the centre of rotation (isocentre), relatively small FOV, and short source to image distance. They provide for flexible programme set up, pulsed fluoroscopy, and spectral filter options. Modern systems have the capability to acquire three-dimensional image data, and operate as cone beam computed tomography (CT) scanners. A 'mini C-arm' is a fluoroscopy system with a relatively small (<45 cm) maximum source to image receptor distance that is used for musculoskeletal extremity interventions alone.

Angiography systems also use a 'C-arm' configuration, but they are often fixed and normally incorporate features linked to the specific requirements of the more complex diagnostic and therapeutic vascular and non-vascular interventional procedures. The procedure requirements include longer fluoroscopy times, many acquisition (digital cine) series, many different angulations and views, extensive use of iodine-based contrast media, use of guidewires and small devices, and the need for high spatial and temporal resolution. Such units have powerful x-ray tubes, many fluoroscopy modes, variable frame rates, comprehensive automatic dose rate control systems, and spectral filters. They also allow for digital subtraction, road mapping, and other post-processing capabilities. Angiography systems typically also have three-dimensional imaging capabilities extending their use to cone beam CT acquisitions.

3.2.2. System features determining x-ray beam quality and exposure levels

(100) Modern fluoroscopy systems operate in pulsed fluoroscopy and other acquisition modes with several pulse/frame rate options (see Box 3.2 for further information). The lowest pulse rate should be used to obtain images of acceptable quality for the imaging task. However, lowering the pulse rate reduces temporal resolution that might be unacceptable for the most rapidly moving organs (e.g. heart or barium video swallowing study), which might require higher pulse rates with or without added magnification.

(101) Modern fluoroscopy systems are also equipped with beam spectrum shaping filters (spectral filtration), usually made of aluminium and/or copper, positioned at the exit of the x-ray tube. Their role is to absorb the low-energy photons, thus reducing the absorbed dose to skin and superficial tissues, but also to increase image contrast by shaping the x-ray spectrum to match the K-absorption edge of barium (at 37.4 keV) or iodine (at 33.2 keV). Other filter materials such as gold and tantalum are also used to modify the spectrum.

(102) In addition to the beam shaping filters, many fluoroscopy systems have semi-transparent 'wedge' filters that can be moved by the operator to selected regions of

the FOV in order to compensate for the lower object attenuation in a region, thus keeping the image brightness constant and maintaining image quality.

Box 3.2. Pulsed fluoroscopy

Modern fluoroscopy systems operate in pulsed fluoroscopy and other acquisition modes with several pulse rate options. Pulsed means that the x rays with pulse widths between 2 and 15 ms are emitted at typically 3, 7.5, 15, or 30 pulses per second (pps) (user selectable), but a larger range of options may be available in modern equipment. The gap between pulses on the display is filled with the last acquired image. The use of short pulses of the x-ray beam instead of continuous emission results in sharper images due to the reduced motion blur. At high pulse rates, typically 30 pps that are similar to the frame rate of the display, observers perceive the rapid sequence of image frames as a continuous motion due to the lag in the human visual system. At pulse rates of 30 pps, the entrance surface air kerma (ESAK) rate at the patient surface may be similar to that with continuous fluoroscopy. The figure shows the variation of the ESAK rate for different pulsed fluoroscopy modes. The expected 50% dose reduction when changing from 30 to 15 pps may not occur as the relationship between pulse rate and radiation exposure is variable, especially among older systems. This results from the fact that the generator may increase the tube current automatically to maintain a constant signal-to-noise ratio. Real dose reductions of approximately 22% have been reported in the past (Aufrichtig et al., 1994; Mahesh, 2001).

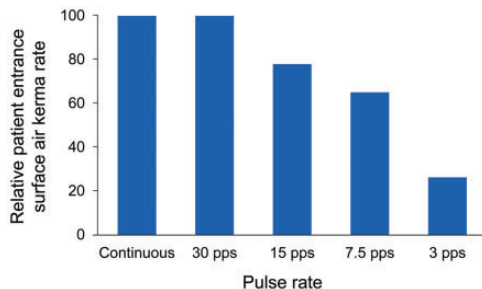


Fig. Effect of pulsed fluoroscopy on patient entrance surface air kerma rate for constant signal-to-noise ratio.

(103) All fluoroscopy systems are equipped with a collimator device to limit the geometric extent of the x-ray field, which may have a circular and/or rectangular shape, matching the shape of the image receptor. The automatic collimator system ensures that the x-ray field is always aligned to the selected FOV, and never extends beyond the image receptor limits. In addition to the automatic collimation, dual-shape collimators are typically available, incorporating both circular and rectangular shutters to be used to modify the field for collimation around areas of

interest. Limitation of the field size to the region of interest is important as it limits the dose to the patient and reduces scatter radiation, thus improving image contrast and also reducing the radiation scattered to staff present in the room.

(104) Modern fluoroscopy systems feature a last image hold (LIH) capability, which is the capture and display of the last acquired frame. This is a useful feature that can reduce the fluoroscopy exposure time, and thus patient exposure, by allowing the image details to be viewed without exposing the patient further. The images remain only until the next fluoroscopy exposure (IEC, 2022a).

(105) Modern fluoroscopy systems have automatic positioning systems, which reduce the amount of fluoroscopy time required to position the system properly for various imaging procedures. Also, a ‘virtual collimator’ is available which allows the operator to manipulate collimator blades while using LIH, thus eliminating the need for fluoroscopy and reducing radiation dose (NEMA, 2016).

(106) Fluoroscopy systems incorporate an ADRC, sometimes referred to as ‘automatic brightness control’ (ABC) in the past for analogue IIs. This device automatically adjusts exposure parameters and the IAK rate to the image receptor to deliver a constant signal intensity at the image receptor, resulting in constant image brightness and SNR at the display despite variations in body habitus. Different ADRC programmes are available to optimise the imaging for different anatomical regions, so the operator should be aware of the options and select the mode appropriate for the imaging task (see Box 3.3 for an example).

(107) Fluoroscopy systems feature different electronic magnifications (also referred to as ‘zoom’ or ‘mag’), which are used to magnify a portion of the image at improved high-contrast resolution. In II-based systems, this is done by changing the electronic focusing inside the II, which results in an increased IAK rate at the image receptor that is inversely proportional to the area of the FOV. Thus, doubling the electronic magnification multiplies the IAK by a factor of 4. FP-based systems also increase the rate as the image is magnified in response to changes in the image matrix size. However, the increase in IAK rate with magnification is less pronounced, as the spatial resolution in a FP system is theoretically independent of the FOV. In practice, the increase in the IAK rate with FOV is vendor dependent, commonly reciprocally related to FOV. The actual relationship should be checked at commissioning to ensure that it is as expected (Section 3.3).

3.2.3. Image display considerations

(108) LIH and cine series hold (CSH) features should be used whenever possible (Section 3.2.2). Some systems allow users to store and replay at least 300 frames of the most recent fluoroscopic imaging sequence with the CSH (Radvany and Mahesh, 2015). This should always be the preferred option to reduce patient exposure, instead of recording radiographic images or a cine series (NEMA, 2016; IEC, 2022a).

(109) Image display monitors have an important role in the visual perception of the images, and therefore an indirect impact on the patient and consequently staff

dose, especially in fluoroscopy guided procedures that require the operator to be close to the patient. Using large (e.g. 60") monitors helps to lower patient dose by reducing the need for magnification mode, thus reducing the patient and staff doses. This also allows the operator to see small vessels from larger distances, thus reducing their radiation exposure (Balter, 2019).

Box 3.3. Example of automatic dose rate control programming

The selection of exposure factors (tube voltage and tube current) follows predetermined curves that are stored in the generator, adjusted for each equipment model and manufacturer (see figure below). While the changeable exposure factors are typically the tube voltage and the tube current, the automatic dose rate controls (ADRCs) in more advanced systems include the filtration added to the tube, the pulse width, and the focal spot size. The fluoroscopy system allows for operator-selectable fluoroscopy modes which use different curves, including standard (normal), low dose, and high dose (high contrast) curves. As patient attenuation increases, the incident air kerma (IAK) rate at the patient increases, while that at the image receptor does not vary. However, the IAK rate at the image receptor normally increases when changing from low dose mode to high dose mode to provide a higher level of image quality.

The ADRC algorithms adjust the exposure factors to maintain the patient entrance surface air kerma rate for fluoroscopy within levels recommended in regulatory guidance, which may lead to degradation of image quality for high attenuation objects such as obese patients, lateral or oblique projections, or thicker body parts.

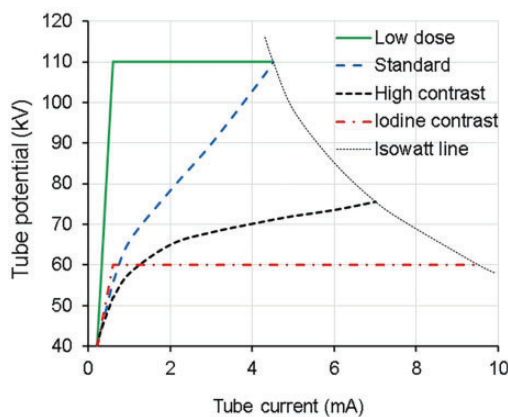


Fig. Example kV vs mA curves for fluoroscopic exposure modes suitable for different imaging tasks. When the limiting entrance surface air kerma (ESAK) rates at the patient are reached, there are sharp discontinuities as the tube potential is increased and the mA is reduced to avoid exceeding the limiting ESAK rate. Source: Colin Martin, University of Glasgow, UK.

3.3. Exposure configuration and optimisation during commissioning

3.3.1. Imaging features and requirements

(110) Fluoroscopy systems provide a selection of pre-configured examinations and patient-specific technical sets (Balter, 2019). Each configuration comprises a set of exposure technique factors and image processing parameters, which are programmable and adjustable to the local practice and user preferences by a vendor representative (application specialist) or a local authenticated user, in collaboration with the hospital medical physicists and experienced representatives of the clinical staff (the core team).

(111) Based on the different image quality requirements for different clinical tasks, protocols differ for application (e.g. cardiac, neuro, vascular, paediatric) and also for different acquisition techniques such as digital subtraction angiography. The configuration parameters for each of these protocols are hidden from users, and can only be modified by a user with elevated access rights to the equipment. Testing and adjustment of these parameters during the commissioning is of great importance. However, it does require clear understanding of the system features, functions, programme architecture, clinical requirements, and operators' preferences.

(112) Protocol configuration should include consideration of the use of an anti-scatter grid, lower tube voltage, optimal use of collimation and wedge filters, and contrast enhancement during image processing. There may sometimes be a clinical need to reduce noise that may require an increase in photon flux using a higher mA. Close attention should be paid to collimation to reduce scatter. For improving visual contrast perception, high-quality monitors and optimal viewing distance are also recommended.

(113) For example, a clinical study requiring visualisation of high-resolution images (e.g. small vessels, fine instruments, etc.) requires a small focal spot size, smaller SID and object to detector distance, small detector pixel size and large matrix, magnification, and good visualisation conditions with large monitors that have high brightness levels. Modern post-processing using fast image enhancement algorithms such as multi-frequency processing improves the visualisation of contrast structures significantly. Such high-resolution dynamic imaging requires higher pulse rates (15 or 30 pps) with smaller pulse widths, as well as special image processing techniques.

(114) The facility core team should create a variety of selectable pre-defined study protocols and acquisition programmes for the procedures commonly performed with each particular fluoroscopy unit, in collaboration with the vendor applications specialist.

3.3.2. Optimisation of acquisition protocols during commissioning

(115) During equipment commissioning, medical physicists should check whether acceptable values have been set for the default acquisition programmes, and necessary adjustments should be made in collaboration with the equipment vendor representative and clinical staff. This includes confirmation of equipment function, checking baseline values of equipment performance in terms of image quality and dose parameters, and using standard phantoms and test objects that represent a range of patient sizes (AAPM, 2012; Stevens, 2021; Lin et al., 2022). An important task at the stage of commissioning is to optimise the system for the clinical tasks, and set these modes as defaults.

(116) Protocol configuration includes proper adjustment of settings customised to give the required image quality and dose saving needs for the clinical task with reference to the DRLs if they exist. This includes the settings for the ADRC system and other programmes for which acquisition parameters are changing.

(117) During the system commissioning and configuration, ADRC settings for different modes and anatomical/clinical programmes should be tested and adjusted; baseline values should be set for the IAK rate at the image receptor, as well as the patient's ESAK rate (AAPM, 2012; IPEM, 2021). Note that there is only an indirect correlation between the image receptor IAK rate and the patient ESAK rate (AAPM, 2012), as the relationship depends on the exposure factor option selected (Box 3.3). Setting appropriate values for IAK rate at the image receptor in fluoroscopy and radiography modes for different fluoroscopy dose modes, pulse rates, and FOVs is one of the most challenging tasks during system configuration (AAPM, 2012; Jones et al., 2014; Stevens, 2021).

(118) The changes in the IAK rate with the fluoroscopy pulse rate (Box 3.2) and FOV also need to be tested during commissioning, and properly adjusted to meet the image quality requirements for the different clinical indications and patient types.

3.4. Establishing equipment performance and quality control programme

(119) QC programmes should be established to evaluate performance of all exposure modes relating to the selection of options that are optimal for specific imaging tasks. QC is an essential component of the dose management QA programme, and requirements are discussed in *Publication 154* (ICRP, 2023). Fluoroscopy equipment QC requires a wide variety of tests to be performed with different frequencies, as described in dedicated guidance publications, and summarised briefly in Table 3.1 (AAPM, 2001, 2012; IPEM, 2005, 2010; EC, 2012; IAEA, 2022a, IEC, 2022a, b). Where appropriate, testing should be performed for all dose/image quality modes and possible magnifications and image acquisition (fluoroscopy and radiography).

Table 3.1. Summary of quality control tests for a fluoroscopy system

Elements of quality control programme	Parameters to be measured
X-ray source assembly	Accuracy and reproducibility of the tube voltage Half-value layer Reproducibility and linearity of the tube output Tube leakage
Collimation and radiation field alignment	Alignment and collimation of the radiation field to the image receptor
ADRC settings and performance	IAK rate at the image receptor and patient ESAK rate for most commonly used modes and programmes
Integrated radiation dose displays (Annex A)	Verification of calibration of KAP meter Verification of displayed KAP and reference air kerma Correction factors for use with RDSR when function is available
Image quality	Noise level Low-contrast detectability High-contrast detectability Image distortion and artefacts
Cone beam CT mode if available (EFOMP/ESTRO/IAEA, 2019)	Dose parameters Geometry characteristics Image quality

ADRC, automatic dose rate control; IAK, incident air kerma; entrance surface air kerma; KAP, kerma-area product; RDSR, radiation dose structured report; CT, computed tomography.

(120) Currently, test objects used for QC tests are not particularly representative of body habitus or the conditions encountered in the clinical setting. More realistic test objects that enable task-based model observer evaluations of system imaging performance may soon become available. It is anticipated that vendors of fluoroscopy equipment will provide a user quality control mode for interventional procedures which will allow for an easier and reproducible QC process without vendor involvement and with clinical processing disabled (NEMA, 2018; IEC, 2022a). This mode will allow for more comprehensive physical tests to be introduced in the routine QC programme.

3.5. Patient dose monitoring and dose audits

(121) Reliable dosimetry of patients is essential for achieving optimisation. In fluoroscopy, dose management is concerned with both stochastic effects and tissue reactions. Thus, modern equipment provides dose data on the operator’s monitor that includes the KAP rate and reference air kerma rate at the patient entrance reference point, as well as their cumulated values (IEC, 2020, 2022a) (see Box 3.4 and Annex A).

Box 3.4. Diagnostic reference levels in fluoroscopically guided interventional procedures

Whilst diagnostic reference levels (DRLs) are very useful for diagnostic examinations, they are much more challenging to implement or interpret in the case of fluoroscopically guided interventional (FGI) procedures because: (i) such procedures are, by definition, therapeutic not diagnostic; and (ii) there is a wide distribution of patient doses for any given examination. Therapeutic interventions vary by severity, complexity, and site and are therefore more or less unique. Interventional procedures demonstrate substantial variability in the amount of radiation used for individual cases as a result of patient, operator, and equipment factors (ICRP, 2017; COMARE, 2021).

Publication 135 recommends that although interventional procedures are therapeutic, the term ‘DRL’ should be retained for use in interventional radiology as the purpose of DRLs is to provide a tool for optimisation, and the adoption of a different nomenclature is likely to result in confusion (ICRP, 2017). However, the publication does recommend that DRLs for interventional procedures should be developed differently from those for diagnostic procedures. One possible approach is to try and determine the ‘complexity’ of a procedure; another is to utilise the concept of advisory data sets. Both are difficult to implement in practice.

Kerma-area product (KAP , P_{KA}) is the preferred metric for DRLs (Annex A). Another quantity that can possibly be used is reference air kerma ($K_{a,r}$) (IEC, 2020) [also referred to as ‘cumulative air kerma’ (CAK) at the patient entrance reference point]. If $K_{a,r}$ is available, it can be used to provide additional information to assist optimisation. For instance, a comparison of P_{KA} and $K_{a,r}$ values can be used to judge the adequacy of beam collimation. Fluoroscopy time and the number of radiographic images obtained as part of the procedure can also be useful for assisting in optimisation of local practices.

The number of patients to include in the dose audit survey depends on the complexity of the procedure and the resources. Larger numbers of patients may be needed for FGI procedures, and preferably the data should be collated from all interventional procedures performed (not just a limited sample).

For further information on DRLs, see *Publication 135* (ICRP, 2017).

(122) All available dosimetry information, along with images and other procedure-related information, should be recorded and stored at the level of modality in a standard format. Modern equipment should be able to record these data electronically in a radiation dose structured report (RDSR) (see Annex B).

(123) The dose management QA programme should include provision for local audits of patient dose quantities for which local or national DRLs are established and for providing patient management/follow-up (ICRP, 2023). However, DRLs are much more challenging to implement for FGI examinations than in conventional fluoroscopy (see Box 3.4 for further explanation).

3.6. Skin dose monitoring and alert levels

(124) In some complex interventional procedures, patient skin and even the underlying bone structures may receive high radiation doses that exceed the dose threshold for tissue reaction (ICRP, 2000b, 2012; Balter et al., 2010; NCRP, 2010; Jaschke et al., 2017). Prevention of injuries and minimising the adverse effects for patients is possible in most cases if interventional specialists are properly trained and pay careful attention to applying the most effective techniques. Dose monitoring and patient follow-up are essential for management of tissue reactions. The best way to predict possible radiation effects is to estimate the distribution of absorbed doses on the surface of the patient's skin and PSD (Box 3.5).

(125) Ideally, information on PSD should be available in real time during the procedure, and notification provided to the operator to modify the technique in order to avoid the skin dose exceeding the threshold for tissue reaction. Alternatively, post-procedure feedback should be provided and proper follow-up programmes established in interventional facilities. Estimation of PSD will require assessment and analysis by a qualified medical physicist.

(126) Procedures associated with radiation doses that might involve a risk of tissue reactions include: embolisation (including chemoembolisation); stent and stent graft placement; percutaneous coronary intervention; radiofrequency ablation; transjugular intrahepatic portosystemic shunt creation or revision; endovascular aneurysm repair; stent placement; complex biliary interventions; and complex, multi-level vertebral augmentation procedures (including vertebroplasty and kyphoplasty) (ICRP, 2000b, 2010, 2013a; Stecker et al., 2009; Jaschke et al., 2020; NCRP, 2023).

(127) PSD can be measured directly using different types of dosimeters, or calculated from measured dose quantities. If that is not possible, it can be estimated from $K_{a,r}$ or P_{KA} (see Box 3.5 for further details).

(128) The QA programme should include an element in which dose values are monitored throughout the clinical procedure, preferably accompanied by a radiation dose management system. The cumulated values should be recorded in the patient medical record after the procedure and kept in the departmental records for review. The operator should be notified when a dose parameter exceeds a pre-defined alert level during the procedure. This does not mean that the procedure should be interrupted, but having been notified about a high dose, the operator might be able to modify some technique elements using options discussed below in Section 3.7.2, and consequently avoid the threshold for tissue reactions. Alerts should preferably pop-up automatically, but if no means exist for setting automatic alerts in the fluoroscopy system, the responsibility for monitoring dose values and notifying the operator should be delegated to an appropriately trained and appointed staff member (Stecker et al., 2009; Jaschke et al., 2020). Suggested alert levels are summarised in Table 3.2 (Stecker et al., 2009; NCRP, 2010). Rarely will it be necessary for a procedure to be stopped due solely to radiation dose, as this will incur a risk with no benefit to the patient. When appropriate, complex clinical procedures may be planned in a staged fashion, with multiple sessions separated by 8–10 weeks, so

that the dose to the skin is fractionated to reduce the likelihood of tissue reactions (Fisher et al., 2021).

Box 3.5. Measurement, calculation, and estimation of peak skin dose

Measurement: Peak skin dose (PSD) can be estimated directly using different types of dosimeters, attached to the entrance surface of the patient: thermoluminescence detectors, slow x-ray films, radiochromic films, metal oxide semiconductor field effect transistor radiation sensors, or scintillation dosimeters (Vañó et al., 1997, 2001; Balter et al., 2002; Fletcher et al., 2002). Radiochromic films have proven to be a suitable solution to measure PSD with an uncertainty of approximately 15–20%, if care is taken for proper calibration and measurement conditions (McCabe et al., 2011; Farah et al., 2015; Greffier et al., 2017). However, this method is time-consuming and expensive, and cannot be applied routinely. Practically, radiochromic film is sometimes used in cases when a complex or prolonged procedure is anticipated (Stecker et al., 2009).

Calculation: PSD can be calculated from the measured dose quantities, geometry, and exposure parameters taken from the radiation dose structured report (RDSR) or other types of dose report, and a medical physicist should be involved in making such assessments (Jones and Pasciak, 2011, 2012). Various dose management systems include PSD estimation. The accuracy of the method depends on several factors, including the calibration accuracy of dosimetric equipment, accuracy of information reported in the Digital Imaging and Communication in Medicine (DICOM) header and proprietary dose reports, accuracy of dose quantities [kerma-area product (KAP , P_{KA}) and reference air kerma ($K_{a,r}$)] measured by the medical physicist, and procedural factors such as rotation of the C-arm during a fluoroscopically guided procedure (Jones et al., 2012). There are several software products for skin dose calculations, most based on the methodology proposed by Jones and Pasciak (2011, 2012), and a few use Monte Carlo simulations of the photon transport. A review performed under the European VERDIC project found considerable differences in implementation, and strong heterogeneities in encoding examination-related parameters in the RDSR and the export of DICOM fields (Malchair et al., 2018). Most of these software products provide post-procedure two- or three-dimensional skin dose maps based on an anthropomorphic phantom library matched to a patient body size and shape (Lee et al., 2010). There are developments to provide real-time information on skin dose and dose rate during fluoroscopically guided interventional (FGI) procedures, with visual presentation of the cumulative skin dose mapped on to an anthropomorphic model (Bednarek et al., 2011; Johnson et al., 2011; Bordier et al., 2015; Rana et al., 2016). The real-time feedback has been demonstrated to have a significant positive effect on operator awareness and enhancing patient safety during FGI procedures (Wilson et al., 2016; Ichimoto et al., 2018).

Estimation: If no means of measurement of PSD is available, $K_{a,r}$ and P_{KA} can be monitored, and alerts set for these quantities. $K_{a,r}$ is the best predictor of maximum skin dose, but it does not always correlate well with PSD, depending

on the procedure type, specific protocol, use of different projections, operator experience, etc. Correlation of PSD with the cumulated KAP is weaker although still good for some procedures, especially if projection does not change during the procedure. However, as the correlation depends on beam area, it is dependent on the procedure (Neil et al., 2010). Fluoroscopy time and number of acquired images are poor predictors of skin injuries (Balter et al., 2002; Pasquino et al., 2018). The correlation between PSD and dose indicators should be assessed for each equipment and procedure type.

(129) Post-procedure dose notification should be provided to the operator in case any of the reported dose values reach the pre-defined trigger levels for patient follow-up and management of tissue reactions. Table 3.2 shows trigger levels as suggested by IAEA’s international web-based voluntary and anonymous reporting system for FGI procedures – SAFRAD (Safety in Radiological Procedures). SAFRAD aims to collect information about procedures exceeding trigger levels, and define more realistic trigger dose indicators for different types of interventional procedure.

Table 3.2. Alert levels during the fluoroscopy procedure and post-procedure trigger levels for patient follow-up (Stecker et al., 2009; NCRP, 2010; IAEA, 2022b, 2023d; NCRP, 2023)

Dose parameter	During the procedure		Post-procedure
	First notification level	Subsequent notification level (increments)	Trigger level for patient follow-up
Peak skin dose	2 Gy	0.5 Gy	3–5 Gy
Reference air kerma	3 Gy	1 Gy	5 Gy
Cumulated air kerma area product	300 Gy cm ² *	100 Gy cm ² *	500 Gy cm ²
Fluoroscopy time	30 min	15 min	60 min

*Assuming a 100 cm² field at the patient’s skin. The value should be adjusted for the actual procedural field size (Stecker et al., 2009).

3.7. Practical advice for optimal performance of fluoroscopy procedures and patient management

(130) Optimisation should consider radiation risk in conjunction with other non-radiation-related risks (e.g. use of contrast media, medications, sedation/anaesthesia, etc.). The optimisation task should not only include the current procedure, but should consider the patient cumulative exposure, including potential future procedures that might be needed. This is especially important for repeated FGI procedures to take account of cumulative skin dose from previous exposure increasing the risk of tissue reactions. Although repair of sublethal radiation skin injury is complete typically within 1 day, repopulation of cells can take several months. Therefore, the proper timing of a procedure and its optimal performance should be balanced

carefully for each individual patient and each clinical situation. The process includes actions before, during, and after the FGI procedure.

3.7.1. Before the procedure

(131) When a complex FGI procedure is proposed, the patient medical and radiation history should be reviewed, and the procedure planned appropriately. Previous diagnostic and therapeutic procedures involving the use of ionising radiation should be reviewed. If necessary, skin doses could be summed over a period of 60 days prior to the procedure for assessment of risk (Fisher et al., 2021). Any relevant diagnostic images should be made available to the operator to reduce the need for additional diagnostic imaging before the procedure; where imaging is needed, a preference should be given to ultrasound or MRI to avoid the unnecessary use of fluoroscopy during the procedure.

(132) Guidelines should be prepared by the interventional team on methods for reducing the potential for skin injuries, such as use of different x-ray tube angulations to spread the skin dose, the length of time left between repeat procedures (angioplasty or other) relating to the patient's clinical condition, and methods for identifying areas of previous exposure in order to assist the minimisation of risk where appropriate.

(133) Departments performing FGI procedures should develop a standard checklist to identify patients at higher risk. Such patients and their carers should have the risks explained carefully, and should be given written information about the procedure and the possible risks. Where there are significant risks of skin injury, the patient should be asked to give written consent before the procedure, and information about the risks could also be included in this form (ICRP, 2013a). An example of such a form is given in Box 3.6. Three groups of patients require special attention in planning the procedure: paediatrics (see Section 5); pregnant patients (see Section 6); and patients at increased radiation risk for skin injury due to genetics or medications (NCRP, 2023).

Box 3.6. Example of language for informed consent for radiation risks before a scheduled complex and potentially high dose interventional procedure [adapted from Stecker et al. (2009)]

You have been scheduled for an interventional (fluoroscopy guided) procedure. This involves the use of x rays for imaging during the procedure and documenting the results. Because of the nature of the planned procedure, it is possible that we will have to use significant amounts of radiation. Potential radiation risks to you include:

- A slightly elevated risk of cancer later in life, not starting until several years after the procedure. This risk is very low in comparison to the normal incidence of cancer.
- Depending on the procedure, sometimes a substantial amount of radiation may need to be used. This could carry a risk of temporary skin reddening or hair loss, but any more severe radiation injury is very unlikely.

You (or your family) will be advised if large amounts of radiation were used during the procedure. If this has occurred, you will be given written instructions requesting that a family member checks the area of skin irradiated during the next 30 days for any redness or other sign of injury.

Sign and date here _____ witness (physician) _____ date _____

(134) Patients at increased risk for skin injury include obese patients (e.g. with body mass index $>30 \text{ kg/m}^2$), those who underwent recent interventional or radiotherapy procedures in the same body region, and those who might have higher sensitivity to radiation exposure. When a repeated FGI procedure is planned, the prior medical history should be reviewed, the patient's skin should be examined, and the patient should be interviewed for previous or current skin reactions. All visible skin changes should be identified with radio-opaque markers, so that their locations can be seen on the fluoroscopic image to aid the minimisation of further exposure to the area. When there is a concern for radiosensitive skin and the patient's condition allows, the planned FGI procedure should be performed at least 8–12 weeks after the previous procedure in the same body area, and after at least 4–6 weeks when a different body area will be irradiated (Balter, 2019).

(135) A standard policy for assessing pregnancy should be in place for facilities performing FGI procedures to avoid accidental exposure of an embryo or fetus (see Section 6). If pregnancy is established and the patient's condition allows, the procedure should be deferred until after delivery (ICRP, 2000a; ACR/SPR, 2018). This is especially the case for procedures in which the dose to the conceptus (embryo or fetus) can exceed 10 s of mGy which include uterine artery embolisations, ovarian vein embolisations, and endoscopic retrograde cholangiopancreatography (Dauer et al., 2012). It is very rare for fetal dose to exceed 100 mGy, the threshold for potential congenital malformations to occur (see Section 6).

3.7.2. During the procedure

3.7.2.1. *The team approach*

(136) Fluoroscopy is an interactive imaging procedure requiring proper use of equipment features to perform the clinical task with the lowest possible radiation dose to the patient and staff members. Interventional operators should undergo comprehensive training in the techniques before performing any procedures, and should be supervised by an experienced operator until they are able to perform procedures by themselves (Keefe et al., 2018; Jaschke et al., 2020). Medical simulators may be used for training in catheterisation techniques and the management of patient dose (See et al., 2016).

(137) In addition to the main operator who has the primary responsibility for the procedure outcome and for patient and staff safety, other team members should

have clearly assigned functions to optimise the procedure time and the use of fluoroscopy and radiography. These include patient comfort, cooperation and positioning; adjustment of the monitor display and the console display; appropriate selection of catheters, wires, and devices; checks to ensure everyone is wearing an appropriately positioned radiation dosimeter (ICRP, 2018b); and considering the use of alternative image guidance such as ultrasound.

(138) Good practice is for the fluoroscopy team to include an appropriately trained radiographer to operate the equipment controls, especially when complex FGI procedures are performed, although this may be done by radiologists or other radiological medical practitioners in some countries. In cases when the controls are operated by radiological medical practitioners performing the procedure, they should be capable of performing this as a multi-task function. They will need to simultaneously manipulate a catheter or administer contrast, evaluate the image on the display, monitor the patient's condition, select the proper fluoroscopy position and projection, select the proper programme from the console, operate the beam, and use the minimum amount of fluoroscopy and number of radiographic images.

(139) Other team members should also play a part in optimisation of a procedure; for example, a properly trained nurse or radiographer can be responsible for proper positioning of the radiological protection screens, and another team member should monitor dose factors and notify the operator when pre-defined levels are reached. Regardless of who operates the equipment, the roles should be pre-defined, functions should be optimised, and the team should be well trained. A pre-procedure 'time out' in which team members run through a checklist should be considered. No person should be present in the room without a clear role. Team cooperation and awareness of radiation safety culture are crucial for the success of an FGI procedure. Image Gently (2022c) provided an example of a checklist including all decisions about a procedure.

(140) Every team member should have sufficient knowledge on how to reduce their own radiation exposure by proper positioning in the room and using the three basic principles of protection: time, distance, and shielding (ICRP, 2023). Radiological protection shields and individual protective equipment should be selected and used properly, as recommended in *Publication 139* (ICRP, 2018b).

(141) A successful procedure is reliant upon patient cooperation. Patients should be briefed prior to commencement of the procedure, and given the time and opportunity to ask questions, so that they know what to expect and how to cooperate. Less cooperative patients (e.g. young children) might need to be sedated if patient immobilisation cannot be achieved by other means. More information can be found in Section 5. The decision should be taken jointly with the patient/family by balancing the risk of sedation and the risk of compromised image quality and procedure outcome.

(142) Potential doses to staff performing interventional procedures from radiation scattered from the patient are also a concern, particularly from long, complex interventional procedures. Aspects relating to occupational protection during such procedures are considered in *Publication 139* (ICRP, 2018b). Occupational exposure in

interventional procedures is closely related to patient exposure and, therefore, management of occupational protection should be integrated with patient protection. Staff need to apply the basic radiation protection principles and make effective use of protective devices. Measures to protect staff should not impair the clinical outcome and should not increase patient exposure.

3.7.2.2. Operator selection of x-ray tube and image receptor position and exposure modes

(143) Factors related to the geometric configuration and exposure mode are selectable by the operator, and influence image quality and patient and staff radiation exposure. Those related to exposure mode have been discussed in Section 3.2.2.

(144) Geometric factors include positioning of the x-ray system in relation to the anatomical region, projection, table height, and focus-to-image receptor distance. In C-arm systems, it is preferable from a radiological protection perspective to keep the x-ray tube under the patient table. The distance between the x-ray tube and the patient should always be maximised to reduce patient dose. In C-arms with the x-ray tube fixed in relation to the isocentre, the patient couch should be kept as high as practicable for the operator to manipulate. In isocentric techniques (e.g. for cardiac interventions), the table height should be selected such that the object of interest is in or close to the C-arm isocentre to allow for best image quality. The image receptor should be positioned as close to the patient as possible; this reduces patient and staff exposure from scatter radiation and reduces geometric blurring.

3.7.2.3. X-ray beam projection and collimation

(145) X-ray beam projection and angulation should be selected to provide the required anatomical visualisation, considering also that staff dose rate is higher at oblique or horizontal projections in which the x-ray tube is on the operator side. Patients' extremities should be kept out of the beam to avoid higher dose rates selected by the ADRC when object thickness is increased. The use of steep angulations of the x-ray beam axis passing through thicker, more lateral sections of the body increases patient dose, and should be minimised when possible. Typically, each 3-cm thickness of additional tissue doubles the dose rate to the patient. For long procedures, the area of skin where the x-ray beam is incident upon the patient should be changed where possible during the procedure by modifying the C-arm angulation to reduce PSD and avoid skin injury.

(146) Proper collimation of the primary x-ray beam will reduce the irradiated volume in the patient and the amount of scattered radiation, which improves the image contrast. This will also reduce any possible overlap of the radiation fields from different projections, thus helping to keep PSD below the threshold for skin injury. Patient and staff dose can be reduced with no loss of image quality by using automatic positioning systems or virtual collimation when available. Image contrast can

be improved by properly positioning wedge filters and other functions of the fluoroscopy system, when available.

3.7.2.4. Protocol selection and adjustment

(147) Optimisation of the clinical procedure requires selection of the best available protocol, tailored to the patient characteristics, to achieve the clinical goal. Communication before and during the procedure is critical. The radiological medical practitioner and radiographer will often need to adjust the examination protocol for both the patient needs (patient size, potential motion concerns, etc.) and the clinical issues (safety, contrast limits, magnification of small body parts, etc.).

(148) The anti-scatter grid should be removed for procedures that result in low levels of scattered radiation (e.g. those involving small children or where body thickness is <10 cm).

(149) High dose rate modes in fluoroscopy should be used only when indispensable and for the minimum time necessary for the procedure. The lowest dose rate mode should be set as a default, with the operator required to manually select the higher dose rate mode only when higher image quality is needed. For example, lower image quality can be tolerated when fluoroscopy is used to navigate insertion of a catheter or tube, and higher image quality is needed for viewing small vessels after contrast administration.

(150) The operator has full control over activating the fluoroscopy or radiography acquisition modes, and should minimise fluoroscopy time and use the minimum number of acquired images consistent with the procedure. Whenever possible, the LIH and CSH function should be used, and storing of the last fluoroscopy loop instead of acquiring radiography or cine images.

(151) Box 3.7 provides a summary of practical advice on optimisation (ICRP, 2013a). This should be included in initial and periodic radiological protection training of medical staff, and preferably provided in written form.

(152) If conventional IIs are used, the use of electronic magnification should be limited to cases when high spatial resolution is needed, which cannot be achieved with the non-magnified image. Whenever available, digital magnification should be used instead of electronic magnification.

(153) Operators should avoid placing their hands or objects such as contrast syringes in the primary beam, as this will increase the dose rate to the patient and the scattered dose rate.

(154) In some minimally invasive vascular and non-vascular interventions, such as in peripheral insertion of a central catheter, endourology, or gastroenterology, patient and staff dose can be reduced by using ultrasound images to guide device placement, thus limiting the use of fluoroscopy to those instances when better image quality is needed to localise the object of interest or monitor procedure development.

Box 3.7. Practical techniques to reduce patient dose

Fluoroscopy dose

- Use low dose rate fluoroscopy mode when possible
- Use low pulse rate fluoroscopy mode when possible
- Remove the grid when performing procedures on small children, thin adults, and thin body parts (<10 cm thickness)
- Minimise fluoroscopy time – consider ultrasound to guide devices and observe motion
- Use the last image hold (LIH) function for image store and review, when possible, instead of image exposure or fluoroscopy
- If available, use a stored fluoroscopy loop for review instead of fluoroscopy

Cine dose and digital subtraction angiography

- Use the lowest dose mode for image (cine) acquisition that is compatible with the required image quality
- Minimise the number of cine series
- Minimise the number of frames per cine series
- Never use cine as a substitute for fluoroscopy
- Cine series can sometimes be replaced by LIH
- When possible, use ‘cine series hold’, also referred to as ‘video loop’, if available instead of performing a cine run

Other factors

- Collimate the radiation beam to the area of interest
- Use accurate collimation for protection of the gonads, rather than gonad shields (see Table 2.2)
- Use virtual collimation if available
- Use wedge filters when appropriate
- Keep the image detector (image intensifier or flat panel) as close as possible to the patient
- Keep the patient as far as possible from the x-ray tube
- Try to avoid steeply angulated projections (especially left anterior oblique cranial)
- Try to vary the C-arm angulation slightly to avoid concentrating the radiation dose at a single site on the patient’s skin
- Use magnification only when necessary on image intensifier systems
- Remember that the dose to the patient increases substantially for large patients, and also for steeply angulated projections

Monitoring dose

- Pay attention to the patient radiation dose display in the procedure room
- If the patient has undergone previous similar procedures, try to obtain information about the previous radiation doses to optimise subsequent procedures

- Track cumulative dose and set dose alerts if cumulative dose exceeds certain levels (such as 3 Gy PSD or 5 Gy cumulative air kerma)

3.7.3. After the procedure

(155) Patient radiation dose reports should be produced at the end of the procedure and archived in the departmental records and patient medical record. The information should be used for performing periodic dose audits and benchmarking the practice against available DRLs, and to indicate when optimisation is needed. Specialised dose management systems storing dose information in a database can enable more accurate and powerful analyses to be performed (Fernandez-Soto et al., 2015; ICRP, 2017; Vañó et al., 2022; IAEA, 2023c).

(156) Departments should establish a programme for follow-up of patients when any of the pre-defined trigger values described in Section 3.6 are exceeded. It is likely that some skin injuries are missed or misdiagnosed because of lack of follow-up. The radiological medical practitioner should write an appropriate note in the patient's medical record, stating that a substantial radiation dose has been administered, and indicating the reason. In this case, clinical follow-up is essential for early detection and management of potential skin injuries (NCRP, 2010; ICRP, 2013a). A standard form would be useful to record the information, possibly with an anatomical sketch on which areas that may have received a high skin dose could be marked.

(157) The patient or their carer should be advised of the possibility of a skin injury due to a tissue reaction, and should be told to examine the beam entrance site 2–4 weeks after the procedure and to notify the operator if any skin changes are seen. An example of post-procedure patient discharge instructions for high dose procedures is given in Box 3.8. Patients who have not notified the operator previously should be contacted by telephone approximately 30 days after the procedure in order to ensure that a skin injury is not missed (ICRP, 2013a).

Box 3.8. Example of post-procedure patient discharge instructions for high dose interventional procedures [adapted from Stecker et al. (2009)]

X-ray usage – one of these two boxes is checked as part of the discharge instruction process:

- ☐ Your procedure was completed without the use of substantial amounts of x rays. No special follow-up is needed because radiation side effects are highly unlikely.
- ☐ Your procedure required the use of substantial amounts of x rays. Radiation side-effects are unlikely but possible. Please have a family member or carer inspect your (back/neck/scalp/....) 30 days from today for signs of skin redness or rash.

Please call ##### and tell us whether or not anything is seen.

(158) If a skin injury is suspected, the radiological medical practitioner should see the patient at an office visit and should arrange for appropriate follow-up care. The physician responsible for the patient's care should be informed of the possibility of radiation effects (Stecker et al., 2009; NCRP, 2010; IAEA, 2023d). In addition, it is recommended that sites where interventional procedures are performed should establish a team that includes a radiological medical practitioner, medical physicist, and radiographer to review protocols in cases when the patient skin dose exceeds certain pre-selected levels. The collection and analysis of data on tissue reactions at a national or international level can contribute to understanding the factors involved, and contribute to guidance for reducing their occurrence.

3.8. Dose and image quality management programme

(159) As outlined throughout this section, the development of a successful dose management QA programme is an essential part of radiological protection and optimisation. Components of the QA programme dealing with dose management should be put in place to enable the optimisation process to progress, and a core team should be established to promote optimisation through reviews of common fluoroscopic procedures. In addition to equipment selection, facility design, maintenance, and QC tests discussed in Section 2 of *Publication 154* (ICRP, 2023) for fluoroscopy guided procedures, QA should include attention to the following components (ICRP, 2013a, 2018b, 2023):

- availability of radiological protection tools, dosimeters, and their use;
- availability of adequate personnel and their responsibilities;
- training in radiological protection (initial and continuing);
- patient and staff dose monitoring and dose audit – a radiation dose management system should be available for effective patient dose management;
- clinical follow-up for high patient radiation doses in relation to skin injury;
- image quality and procedure evaluation;
- reporting and QA for unintended or accidental exposures; and
- training in radiological protection to include ethics, teamwork, safety culture, and communication, as discussed in ICRP (2024).

(160) The complexity of the dose management QA programme and the level of performance and optimisation will depend on the arrangements that are in place for each of the aspects described in *Publication 154* (ICRP, 2023): professional skills and collaboration; methodology and technology; and organisational processes and documentation. Box 3.9 presents the arrangements that should be in place for fluoroscopy facilities at different levels of development: C (basic), B (intermediate), and A (advanced).

Box 3.9. Arrangements that should be in place for fluoroscopy facilities at different levels of development and complexity

C: Basic

- Requests for fluoroscopy procedure include reason for referral and some clinical history of patient
- Operators knowledgeable on equipment features, programmes, and modes
- Operators and all personnel involved trained to perform procedure with minimum amount of radiation for patient and staff
- Radiological protection personal protective equipment available and used properly
- Selectable pre-defined study protocols and acquisition programmes for common clinical conditions available and optimised for the clinical tasks performed with the equipment
- Pulsed fluoroscopy, pulsed image acquisition modes, beam shaping filters, and ‘wedge’ filters in use
- Different automatic dose rate control (ADRC) programmes available for different anatomic regions
- ADRC settings for different modes, and anatomical/clinical programmes tested, adjusted, and baseline values of incident air kerma rates at the image receptor set at commissioning
- Lowest dose rate fluoroscopy mode set as default
- Digital subtraction angiography function available for fluoroscopically guided interventional (FGI) vascular procedures
- Regulatory limit for the maximum patient entrance surface air kerma rate met at commissioning
- Last image hold function available and used
- Quality control (QC) tests to characterise system performance carried out at least annually by a qualified medical physicist or x-ray/service engineer
- Regular constancy checks performed by a local qualified staff member (e.g. medical physicist/radiographer/x-ray engineer)
- Dose display available and report of cumulated values for FGI procedures
- Verification of calibration of dose displays performed as a part of QC
- Local patient dose audits for a common protocol performed by a trained staff member
- Cumulated patient dose values recorded after the procedure in the departmental records and patient medical records
- Follow-up programme established for patients at risk of tissue reaction set if dose values exceed pre-defined trigger levels

B: Intermediate

- Requests for fluoroscopy procedures include reason for referral with clinical history of patient, including pre-procedure diagnostic imaging and information on all previous FGI procedures available in the electronic medical record

- Use of pre-procedure checklist for procedure optimisation by core clinical team
- Standard review process exists to identify patients at higher risk, obtain written consent before FGI procedures, and plan procedure properly
- Protocols for common clinical referrals used for the same clinical indications throughout facility agreed
- Clear procedures set for selecting the most appropriate fluoroscopy system available in the organisation for answering a full range of clinical questions
- ADRC based on fully automatic adjustment of exposure parameters
- Dose display available and report of cumulated values exportable in a standard format for all fluoroscopy procedures
- Features such as ‘spot fluoroscopy’, automatic positioning systems, ‘virtual collimator’, and ‘live zoom’ available and used
- Store and replay function available and used
- Large extra bright image monitors utilised for FGI procedures
- Cone beam computed tomography utilised and optimised for FGI procedures
- Road mapping used for FGI vascular procedures
- Optimal system performance set in collaboration between vendor representatives and local core team
- Comprehensive QC programme established for testing equipment performance in terms of image quality and dose parameters using standard phantoms and test objects, representing a range of patient sizes
- The scope and content of the QC programme, the limiting values, and the frequency of testing at appropriate levels for the intended clinical use of the equipment
- Information about peak skin dose and/or skin dose mapping available in real time during the FGI procedure and recorded after the procedure
- Alert levels set and procedure established to monitor dose values throughout the procedure and notify the operator

A: Advanced

- Consistent nomenclature and naming of clinical imaging protocols throughout organisation, across multiple facilities and equipment
- Harmonised performance settings for all fluoroscopy systems of similar type and uniformity of performance between different systems in multi-facility, multi-site organisations, and multiple radiological medical practitioner groups
- Process of core team continual review and assessment of protocols in place
- Near-miss and error tracking with systems improvement processes
- Application of dose management system to store dose data and analyse performance
- Task-based model observer evaluations of system imaging performance established
- Comprehensive system for patient follow-up with training of all healthcare practitioners involved in different stages of the patient clinical pathway

4. MULTI-DETECTOR COMPUTED TOMOGRAPHY

(161) Key points in this section:

- Protocol optimisation can result in significant dose reduction, while maintaining the required diagnostic level of image quality, but achieving this result depends on appropriate selection of scanning parameters and an understanding of the interdependence of the exposure parameters.
- Lower noise levels are often required to provide sufficient image quality for investigating thinner patients because of the absence of adipose tissue between organs, particularly when viewing low-contrast anatomy.
- Thin CT slices enable versatile volumetric three-dimensional image representations and can improve contrast resolution between small structures and the background when the slice thickness is similar to the dimension of the structure; however, the noise level will be higher, which may be acceptable if the final reviewed image data has sufficient image quality.
- Tube-voltage reduction may enable radiation dose reduction by improving the contrast-to-noise ratio (CNR) for iodine contrast studies, but typically involves a compensatory increase in tube current to reduce the noise level and achieve acceptable clinical image quality.
- IR and deep-learning-based image reconstruction (DLIR) have the potential to produce better image quality and mitigate image artefacts, so that protocols may use lower dose settings to obtain acceptable clinical image quality.
- Automatic tube current modulation (ATCM) accounts for differences in patient size and tissue attenuation. It adjusts the mA to maintain a similar level of image quality throughout a scan; however, CT operators need to understand concepts on which mA adjustments are based, and that image quality references vary between vendors and scanner models.
- For cardiac imaging, CT scanners can be set up to trigger scans at pre-selected phases of the cardiac cycle determined from the electrocardiogram (ECG), and this can provide good image quality at relatively low doses with low and stable heart rates.
- Protocols should be set up initially for examinations that are performed frequently and those that are for urgent indications. The level of image quality, scan parameters, and reconstruction settings should be agreed among the professionals involved.
- Scan protocols should be reviewed periodically, and protocol development should be a continuing process with measurements of dose and image quality being made to assess the impact of changes.

4.1. The increasing use of computed tomography

(162) Since the first clinical images in 1971, CT scanning has increased steadily in importance as the sophistication, speed, and flexibility of equipment and software have evolved. Reconstructed CT images show cross-sections through the body, so unlike other forms of imaging, the images of overlying tissues are not

superimposed. As a result, CT has reduced or eliminated exploratory surgeries, and there is greater potential for identification of abnormal pathology and changes in tissue structure. However, these additional capabilities are usually accompanied by increased radiation exposure. Studies of radiation doses to patients from around the world indicate that where CT scanners are in use, 50–70% of the dose from medical imaging procedures arises from the CT component (Mettler et al., 2008; Hart et al., 2010; NCRP, 2019b). Moreover, the number of CT scans continues to increase in many countries with the demand for additional clinical information provided by three-dimensional volumetric image data and post-processing (Dovales et al., 2016; Bly et al., 2020). Evidence of an association between malignancy and doses from CT scans of children is becoming more compelling (de Basea Gomez et al., 2023). Wide variations in dose are observed in large dose surveys even among facilities using similar CT scanner models and for similar scan indications (Mettler et al., 2008; Martin and Huda, 2013; Shrimpton et al., 2014; Ekpo et al., 2018; Smith-Bindman et al., 2019). Dose levels continue to be reduced both by vendor equipment and software improvements and by educational programmes in many countries as a result of raised awareness about the need for optimisation (IAEA/WHO, 2012). However, wide variability in CT doses still exists among countries and continents for similar clinical indications (Smith-Bindman et al., 2019). These differences are related to available CT technology, personnel training on dose optimisation and patient workflow, and the lack of adequate dose management as part of the QA programme. There is still much to be achieved in terms of optimisation of protection worldwide, which requires consideration of the existing resources and challenges in each region (Vassileva et al., 2015; Kanal et al., 2017; Matsunaga et al., 2019).

(163) As with other imaging equipment, when a new CT facility is set up or an older system is replaced, selection of the appropriate scanner should be carried out by a multi-disciplinary team of radiological professionals (ICRP, 2023). The number of slices ranges from 16 upwards, and the beam coverage in terms of the length of anatomy imaged in a single axial rotation can vary by a factor of 4–5. Other factors that affect performance are the sensitivity of the detectors and the reconstruction method, which will have a decisive effect on clinical image quality and thus indirectly on the required level of dose (Vassileva et al., 2015). Apart from specifications for the CT scanner itself, ancillary equipment such as workstations, software, or other clinical application platforms should be powerful enough to handle the large numbers of images generated, and there should be a maintenance contract in place sufficient to ensure continual operation. Specification, site planning, and purchase of CT equipment all require careful consideration of the cost and benefit (Mahesh and Hevezi, 2010).

(164) The next step is the optimisation of CT protocols, with potential dose reduction while maintaining acceptable image quality, and this will depend on appropriate selection of scanning parameters (both acquisition and reconstruction). Significant dose reduction is sometimes possible, but it is necessary to understand the interdependence of the various parameters in order to achieve this. Sufficient support and training for users from applications specialists and medical physicists are

essential to ensure that advantage is taken of all the CT capabilities provided. Multiple dose reduction features are incorporated into new CT scanner models, but unnecessarily high doses can be delivered if parameters are set incorrectly and/or multiple passes through a body part are performed unnecessarily. The quantities used to record patient dose that are displayed on scanner consoles are the volume CT dose index (CTDI_{vol}) and dose length product (DLP) (Box 4.1). Tissue reactions in the form of skin injury and hair loss are rare, but have been reported during CT perfusion measurements either combined with digital subtraction angiography (Imanishi et al., 2005) or from poor understanding of tube current modulation functionality (ICRP, 2007a; Martin et al., 2017).

Box 4.1. Computed tomography dosimetry quantities (International Commission on Radiation Units and Measurements terminology given in Annex A)

The computed tomography dose index (CTDI) and dose length product (DLP) are the quantities used for evaluation of CT scanner doses.

CTDI: CTDI is the integral of the CT axial air kerma profile along the z axis of rotation of the CT scanner for a single rotation, divided by the nominal width of the beam (IAEA, 2007). By convention, CTDI is measured with an ionisation chamber, 100 cm in length.

Scanner output: The CTDI measured free in air provides a record related to scanner output.

Volume averaged CTDI (CTDI_{vol}): CTDI measured in standard polymethylmethacrylate cylindrical phantoms representing the head (16 cm diameter) and body (32 cm diameter) provides measurements that relate to the doses to patient tissues. Measurements made at the centre and periphery of the phantoms are weighted 1:2 to obtain an average weighted CTDI. An adjustment for the pitch of helical scans is made to derive a CTDI_{vol} that is displayed on scanner consoles (Section 4.2.4).

DLP: CTDI_{vol} can be multiplied by scan length to derive DLP that relates to the dose from a complete CT scan, which is also displayed on CT scanner consoles.

Size-specific dose estimate (SSDE): CTDI_{vol} assessments are based on standard phantoms and take no account of differences in patient size; this varies considerably, especially in the paediatric age range. Correction factors can be used to derive SSDE values based on the dimensions of individual patients (AAPM, 2011a, 2014, 2019a). SSDE values are already displayed on scanner consoles in new scanner models.

(165) All CT scanners must be covered by a comprehensive programme of QC tests, starting from the acceptance and commissioning phase with a new scanner, and including comprehensive regular tests by medical physicists and daily basic QC by radiographers (ACR, 2022; ICRP, 2023). The impact that exposure parameters have on patient dose, or potential issues with system performance hindering diagnostic image quality, will go undetected unless scanner performance is characterised,

and dose levels and image quality are monitored. The scientific skills of the medical physicist in measuring, analysing, and interpreting these test results, combined with the clinical experience of the radiologist or other radiological medical practitioner and radiographer are crucial in this process. The information gained will play a major role in optimisation of radiological protection and keeping CT doses at an acceptable level (ICRP, 2000c, 2007a).

4.2. The computed tomography image

4.2.1. Computed tomography numbers, noise, slice thickness, and contrast

(166) As with all other x-ray imaging techniques, CT image contrast is determined based on x-ray attenuation of the target material or tissue. However, the CT contrast scale is calibrated based on the attenuation of water. More specifically, CT contrast is defined in terms of CT number in Hounsfield units (HU), describing the linear attenuation of x rays in the target relative to the linear attenuation of x rays in water. Water is set at zero (0 HU), and air – with practically zero attenuation – is set at -1000 HU.

(167) The diagnostic value of CT images does not change appreciably when the dose level is increased above the required level for a specific clinical indication (aside from potential incidental findings) (Fig. 4.1). Therefore, a proper definition of required clinical image quality is needed for optimised CT imaging. Basic objective measures of image quality, such as image noise and CNR, are relatively easy to perform, but do not capture all of the features relevant to making a correct clinical diagnosis. An approach might be to require specific noise levels for designated diagnostic tasks.

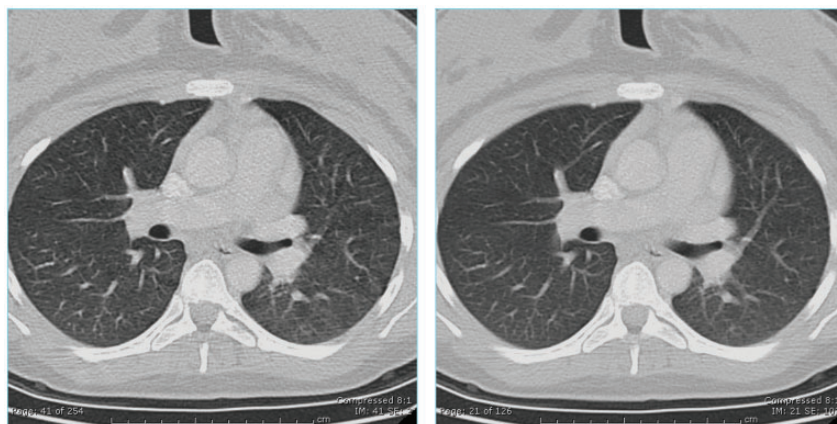


Fig. 4.1. Computed tomography (CT) chest images with contrast taken at 120 kV. The image on the left is with the standard exposure and the image on the right has double the mAs. The difference in quality between the two images is slight and there is no gain in diagnostic information from the higher exposure. CT exposure factors are strongly dependent on patient size. Source: K. Applegate, Department of Radiology, University of Kentucky, USA (retired).

(168) However, ‘optimal’ image quality involves a combination of quantitative metrics including noise, observer perceptions, and training and experience of the interpreter, and depends on the task and type of patient. For instance, imaging of paediatric or thin adult patients may require a lower noise level compared with larger patients because of the absence of adipose tissue between organs and tissue planes and the smaller anatomical dimensions, particularly when viewing low-contrast anatomy (Wilting et al., 2001; McCollough et al., 2002; Boone et al., 2003), but low dose options with higher noise are sufficient in some circumstances (see Fig. 5.3).

(169) As a rough estimate of the dose reduction potential in paediatric body CT scans, the mAs can be reduced by a factor of 4–5 from adult techniques to infants, while for obese patients, it might be increased by a factor of 2 (McCollough et al., 2002). This will be discussed in a later section when ATCM is considered.

(170) If the thickness of the reconstructed image is reduced, a higher mAs will be required to provide the equivalent SNR within the width of the thinner slice. In modern CT scanning, image data are often acquired with thin slices that have approximately the same voxel dimension in the x, y, and z directions (i.e. isotropic resolution). This enables subsequent multi-planar reformats, modality image co-registration, annotation, and/or three-dimensional review to be performed by radiologists, other radiological medical practitioners, or radiographers. These thin source image reconstructions will have higher image noise levels than are seen in the final reformats with thicker slices or three-dimensional visualisations. For a given mAs, the use of thinner slices increases image noise, but can improve the contrast resolution between small features and the background when the slice thickness is similar to the dimensions of the features by reducing the contrast averaging that results from the ‘partial volume effect’.

(171) CT contrast media typically involve iodine-based compounds (ACR, 2021). The injected intravenous contrast media will increase attenuation of arteries and/or veins in CT angiography scans and highly perfused tissues in contrast-enhanced CT scans, aiding the identification of lesions. Contrast media are also used to study tissue function, through recording images before and after administration of the contrast medium (pre-contrast and post-contrast), or as a dynamic scan (e.g. in perfusion studies with a sequentially acquired series of images). Strict timing of imaging is required with respect to the passage of contrast in order to achieve a satisfactory result when the contrast enhancement is at its peak for the specific organ and the patient’s physiological status. This is particularly important for paediatric patients (Mortensen and Tann, 2018) and when imaging targets with rapid biokinetics (e.g. cardiac or coronary CT angiography). The higher contrast properties of iodine allow lower tube potential (and lower radiation dose) protocols in CT angiography to be an effective method of optimisation. CT angiography examinations are usually short or ultrashort, so the volume of injected contrast is lower than in conventional CT. Contrast media can be administered safely at room temperature without increased risk of extravasation, although both allergic reactions and renal contrast nephropathy carry real but very low risks (ACR, 2021).

4.2.2. Scan projection radiograph and scan range

(172) In order to select the range for a CT scan, a low dose scan projection radiograph (SPR) is recorded with the x-ray tube held in a fixed angular position while the patient is transported through the gantry (z-axis). A variety of terms are used for the SPR by different vendors, namely scout view, topogram, surview, or scanogram, and the projection chosen can be antero-posterior (AP), PA, and/or lateral. Furthermore, a single or double SPR may be required to set up the scan. The range of the scan in the longitudinal (z) direction, the axial FOV, and optional scan tilt angle (for most equipment) can then be selected on the SPR image, and the patient positioned automatically to scan the selected regions. The preference on the SPR direction and number of SPRs needed before the actual CT scan varies according to the vendor, scanner model, scanner software version, and the anatomical part of the body to be examined. It is important to be aware of the SPR recommendation because SPR has a direct effect on the ATCM and automatic tube voltage selection (ATVS) performance, and – as a result – on patient dose and image quality.

(173) During routine scans of the brain, the gantry may be tilted to reduce the radiation dose to the eyes; for this, a lateral SPR is used (Yeoman et al., 1992; Heaney and Norvill, 2006; Nikupaavo et al., 2015). In the absence of organ dose modulation (see Section 4.4.4) and the ability to tilt the gantry, the protection of the lens of the eye in head CT scans can also be implemented by tilting the patient head forward using a support cushion of light-foam radiotransparent material placed under the occipital part during the scan (Van Straten et al., 2007). This method necessitates the patient being able to tilt their head accordingly, which may not be an option with trauma or mobility compromised patients. Modern CTs may also offer organ dose modulation to reduce dose to the eyes. The use of shielding on the eyes is discouraged due to suboptimal effects on image quality, overall image acquisition, and patient acceptance.

(174) During a helical CT scan, additional data and, consequently, small amounts of additional rotational irradiation are required at the beginning and end of the scan range for image reconstruction. The additional exposure, referred to as ‘over-ranging’, increases with pitch size and with applied beam collimation (Section 4.2.4). Modern CT scanners are equipped with dynamic collimation using moving beam shutters that will attenuate parts of the x-ray beam at the beginning and end of helical scans to limit the additional exposure. The potential amount of over-ranging is more relevant in dose optimisation when the exposed organ outside the planned region is radiosensitive (e.g. the thyroid in head scans of paediatric patients or younger adults) and can be estimated using radiochromic film.

(175) The radiation exposure to a patient is mainly dependent on the applied dose level [estimated through CTDI_{vol} and size corrected as size-specific dose estimate (SSDE)] and the anatomical length of the exposure to the body, including repeat passes through it (measured by DLP, Box 4.1). Therefore, the scan range should be limited to the region of interest within the body in order to avoid unnecessary radiation dose to organs outside the target range. The boundary definition based

on the individual scan indication is particularly important for paediatric patients, who are, in general, more radiosensitive and in whom organs are in closer proximity.

(176) When using ultra-low dose imaging protocols in CT, the radiation exposure from the SPR may be of the same order of magnitude as the helical scan (Schmidt et al., 2013). This emphasises the need to optimise the whole CT examination including the SPR. Optimisation may involve use of a single SPR instead of two SPRs (AP/PA and lateral) or applying a lower mA. However, vendor recommendations should be followed to ensure that the image signal is adequate for proper ATCM and ATVS functionality (Section 4.4). In certain scanner models, it is possible to apply additional tin filtration to reduce the SPR radiation dose significantly.

4.2.3. Tube potential and filtration

(177) CT scanners use a heavily filtered beam (many millimetres of aluminium equivalent), and tube potentials between 70 and 150 kV can be applied, depending on the patient size, morphology, intended clinical task, and whether iodinated contrast is used.

(178) High tube potentials are required for scanning highly attenuating regions in larger patients to avoid photon starvation, but lower tube potentials provide better contrast for increased iodine concentrations and for smaller patients (Rampado et al., 2009). Values of 100 kV or 80 kV increase the CNR for iodinated contrast in vascular tissues by 25% or 65%, respectively (Itatani et al., 2013; Taguchi et al., 2018). Low kV protocols have significant potential for radiation dose reduction and improving image quality in CT angiography (Talei Franzesi et al., 2018) and detection of vascularised liver tumours (Marin et al., 2009). This is a challenge with larger patients and less-powerful CT scanners because of the more limited x-ray penetration (Aschoff et al., 2017). However, some modern CT scanners can overcome this limitation by offering tube currents up to 1300 mA with lower kilovoltages (Lell and Kachelriess, 2020). Guidance on manual selection of kV settings for patients of varying size is given in Box 4.2.

(179) A lower tube potential will decrease patient dose significantly if the same tube current (mA) is maintained, but the noise level will rise as the x rays are attenuated more heavily, so it may be necessary to increase the mA to some extent to recover image quality in terms of noise. The scanning of phantoms containing iodine contrast solution can be used as a metric to monitor image quality and assess the appropriate increase in mA as kV is reduced for structures enhanced with contrast media. The image quality advantages of low tube potential are limited for soft tissue structures with little or no contrast enhancement. Thus, the image quality without contrast enhancement is related almost entirely to noise level. Image quality, in terms of low-contrast visualisation and noise level, and patient dose should be monitored when making a change for non-contrast procedures.

(180) Tube potential can be selected manually depending on size for each patient in a similar manner to radiography examinations. However, most companies now

offer the option to use information from the SPR to optimise tube potential automatically as well as mA (Winklehner et al., 2011). Clinical studies have demonstrated that scanning with ATVS can provide images with improved contrast at reduced patient doses (Mayer et al., 2014).

Box 4.2. Choosing the tube potential for a computed tomography scan

The optimum tube potential depends on body size, and use of low tube potentials is more advantageous for examinations using iodine contrast. Recommended tube potentials are given here in terms of the sum of antero-posterior and lateral body dimensions in cm (Ranallo, 2013; AAPM, 2022).

Head scans	kV	Body scans, dimension	kV
Paediatric 0–2 years	70–80	Paediatric; <44 cm	70–80
Paediatric 2–6 years, with contrast	80–100	Paediatric and adult; 44–60 cm	100
Paediatric 2–6 years, no contrast	100–110	Medium and large adults; 60–80 cm	120
Adult, with contrast	100–120	Extra large adults: 80 cm	140
Adult, CT perfusion	80–90	Adult upper thorax through shoulders	120
Adult, no contrast	100–120		

CT, computed tomography.

N.B. These values provide guidance but will not be universally appropriate because of differences in CT scanner models. The inherent filtration varies with the CT scanner, so the x-ray spectra will also vary. Moreover, some new scanners have the capability to generate tube currents over 1000 mA with lower kilovoltages, enabling their use with larger patients, when appropriate.

(181) Patients are round (infants and young children) or oval (adults) in cross-section, and when they are irradiated by the fan-shaped x-ray beams in CT scanners, photons passing through peripheral regions of the body at the edge of the fan beam will not pass through as much tissue as those transmitted through the centre. Therefore, the x-ray beam intensity from the peripheral regions would potentially be much greater, and this would create a large dynamic range in intensity at the detector, as well as giving higher radiation doses to superficial tissues. Therefore, beam shaping filters that are thicker towards the edge, having a cross-section similar to that of a bow-tie, after which they are named, are placed in front of the beam. Bow-tie filters reduce beam intensities at the periphery to match the greater attenuation at the centre of the body, producing a more homogeneous distribution of radiation within the body, and so give better uniformity of noise within the image (Boone, 2009). They are designed based on the assumption that the patient is at the isocentre, and the shape and composition of the filters varies with the vendor.

Some vendors have multiple bow-tie filters that can be selected by the user, so it is important that the filter is matched to the body region being imaged. The FOV used for head examinations will be smaller and the shape of the bow-tie filter narrower than that for the body.

4.2.4. Helical scanning, pitch, and beam collimation

(182) CT scanners have a matrix of detectors registering x rays from the fan beam geometry across the circumference of the gantry (providing the data required to reconstruct an image of a slice through the patient), and along the scanner z-axis to allow multiple slices to be imaged simultaneously. The x-ray beam is collimated so that it is incident on the required width of the detector array along the z-axis (e.g. N detectors of thickness T). The patient couch is moved through the CT gantry, so the x-ray beam follows a helical path around their body, collecting data continuously. If the couch moves through a distance l along the z-axis during one tube rotation, and this is equal to the width of the x-ray beam along the z-axis ($N \times T$), the pitch p of the helical scan ($p = l / (N \times T)$) is 1.0. Helical CT scans require interpolation between data from different projections along rotations during image reconstruction (Fig. 4.2). For CT scanners in which the tube current is set manually, increasing the scan pitch could, in principle, reduce patient dose if the tube current remained constant. However, all modern CT scanners have an ATCM function to give a selected level of image quality (Section 4.4), and when this is used, pitch has little effect on patient dose (Ranallo and Szczykutowicz, 2015). However, larger pitch values may give greater additional exposure from over-ranging (Fig. 4.2), although in modern scanners with dynamic collimation, the additional dose from over-ranging is constant (Longo et al., 2017).

(183) Some CT vendors use an ‘effective mAs’ equal to the mAs divided by the pitch. When the operator sets an effective mAs, the variation of pitch is compensated by changing tube current or rotation time to maintain the same image quality. A lower pitch or a longer rotation time can provide an option for imaging larger patients by enabling larger effective mAs values to be used. However, both will increase the scan time, which may create a challenge in faster scans (e.g. in chest region and arterial phase scans where the biokinetics are rapid and there may be a risk of losing the period of optimal enhancement). For paediatric scanning, the gantry rotation speed is often set at ≤ 0.5 s to decrease the chance of motion artefacts.

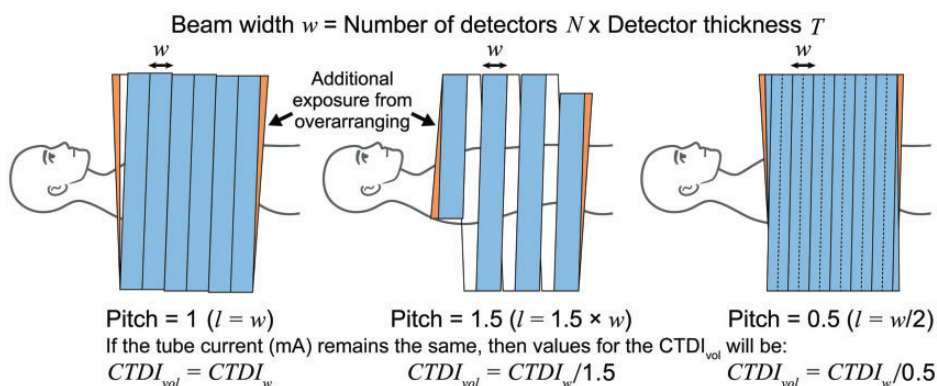


Fig. 4.2. Examples showing the computed tomography (CT) beam trajectory for scans with different pitches. The additional partial rotations at the start and end of the scans are required for image reconstruction. Additional parts of the body not being imaged, highlighted by a darker shade, will be irradiated if there is no dynamic collimation. The additional exposure is referred to as ‘over-ranging’ and is greater for larger pitches (e.g. pitch >1.5). The applied pitch may be >3.0 with dual-source CT scanners. Source: Colin Martin, University of Glasgow, UK.

4.3. Image reconstruction

(184) Filtered back projection (FBP) is the analytical method that has been used for reconstructing CT images since the launch of CT scanning. In essence, this comprises back projection of all the profiles collected at the respective angles, and accumulation of the data in an image matrix. However, a high-pass mathematical filter must first be applied to the data in order to provide acceptable cross-sectional images and to avoid degradation of details. FBP enables images of adequate quality to be reconstructed rapidly for viewing. However, the images tend to have high noise levels, although this depends on the filter kernel used, and poor low-contrast detail detectability in some clinical situations, as well as being prone to artefacts. Filter kernels used in FBP are vendor-specific and typically cover a set of filters ranging from smooth to sharp image representation. Choice of the appropriate filter is important for providing the type of image required for each specific clinical application.

(185) IR methods are proprietary techniques that are available in modern scanners as additional image reconstruction and enhancement methods. In the IR process, an initial image is produced that may be through FBP. Next, simulated raw-data projections are computed in forward projection using this image. These simulated projections are then compared with the original measured raw data to build a correction term based on the differences. A new image is then created through back projection of a correction term. The process goes through a number of iterations and, depending on the modelling accuracy (especially in forward projection), may require high

computing power. Most IR techniques enable the noise level in images to be reduced, and help to suppress artefacts.

(186) The primary aim of IR is to lower the noise level in the images. The operator has two choices when IR is available: to scan at the same original dose (as established for the protocol with FBP) obtaining better image quality (less noise and fewer artefacts), or to scan at a lower dose but aiming to achieve an image quality equivalent to that from the FBP reconstruction (Hara et al., 2009). The potential for dose reductions of tens of percent has been reported in the literature depending on the scan protocol and CT vendor (Willemink et al., 2013b; Morimoto et al., 2017; Mello-Amoedo et al., 2018; Zhang et al., 2019).

(187) If a scanner has the facility for IR, it should be used when it can reduce radiation exposure while maintaining adequate clinical image quality and reducing structured noise artefacts. Vendors offer options with different strengths or levels of IR, basically giving more or less noise reduction. Evaluation of IR options requires detailed analysis of task-based performance, as well as spatial resolution and noise magnitude and texture (AAPM, 2019b).

(188) IR users need to be aware that these methods may cause changes in image texture leading to a blotchy appearance (Leipsic et al., 2010), although this may not be an issue with more recent algorithms. Higher iteration strengths may cause changes in image texture and a reduction in low-contrast resolution (Prakash et al., 2010; Schindera et al., 2013; Willemink et al., 2013a).

(189) Radiologists or other radiological medical practitioners accustomed to FBP images may initially find the unfamiliar appearance of IR images off-putting, and question their diagnostic accuracy. The settings (IR level and reconstruction filters for each clinical protocol indication) should be agreed by the radiological medical practitioners at the facility, and any modification in the level of IR and adjustments in exposure level should be made in stages to ensure that the radiological medical practitioners interpreting the images are deriving a benefit from the changes made.

(190) DLIR has emerged as an alternative to FBP and IR. As DL is a subset of ML, DLIR can also be classified as AI-based CT image reconstruction. DLIR seeks to solve similar image reconstruction problems to IR, namely to enhance image quality by lowering the noise level and reducing artefacts while preserving spatial resolution and contrast appearance (Singh et al., 2020; Arndt et al., 2021; Mohammadinejad et al., 2021). With faster computational speeds, this combination has significant potential, and some vendors also offer different flavours of DLIR adapted to anatomical part or several reconstruction levels, similar to IR. An example of the traditional FBP, digital radiography, and DLIR from the same raw data in CT is shown in Fig. 4.3.

(191) However, all new reconstruction methods and all new techniques together should be validated appropriately for the clinical indication. The precautions related to clinical validation are important because these new methods carry non-linear characteristics which render them more complicated than traditional FBP. DLIR methods are usually trained in the factory, potentially with cohorts of patients that

may not fully represent the local patient cohorts or disease prevalence in the region. A local validation period is recommended during which raw data are reconstructed with the settings used as standard in the clinic in parallel with DLIR for a selected patient group. The validations should be carried out on a variety of patients with varying scan parameters. Analysis of the images by the radiologists and core team at the inception can help the successful implementation of these new reconstruction methods.



Fig. 4.3. An example of (A) traditional (filtered back projection; standard filter), (B) iterative reconstruction (ASiR-V 50%) and (C) deep-learning-based image reconstruction (true Fidelity High) from the same raw data in a neurological brain scan performed with GE Revolution computed tomography for a 5-year-old child. The scan was performed with a single 0.35 s axial rotation with 16 cm z-coverage, 120 kV, 0.625-mm slice thickness, volume averaged computed tomography dose index of 20.7 mGy, and dose length product of 330 mGy cm. The background noise values [standard deviation in Hounsfield units (HU)] in the images were 9 HU in A, 6 HU in B, and 3 HU in C. Images courtesy of Mika Kortensniemi, HUS Diagnostic Center, New Children's Hospital, Finland.

4.4. Automatic tube current modulation

4.4.1. How it works

(192) For a given tube potential, the tube current determines the number of photons emitted, and therefore the dose to the patient. A major technological development to aid in optimisation of CT has been the inclusion of facilities to modulate the tube current automatically to take account of variations in the attenuation of patients' body tissues (Kalra et al., 2004; McCollough et al., 2006). These allow both for differences in patient size and for variation in tissue attenuation. ATCM or AEC is designed to maintain a similar level of image quality throughout a scan, and can reduce doses to individual patients by 30–60% when used effectively (Mulken et al., 2005; Rizzo et al., 2006; Lee et al., 2008; Söderberg and Gunnarsson, 2010). The tube current is varied as the scan progresses along the length of the patient (z axis), with higher levels used for the thicker lateral shoulder and hip regions, and the

current reduced where the soft tissue attenuation is lower in the neck, thorax, and lower extremities. In addition, the tube current can be varied as the x-ray tube rotates around the patient, with the smaller diameter AP/PA directions receiving lower exposures than the lateral direction.

(193) CT operators need to be aware of how ATCM systems operate, and understand concepts on which they are based, as these are not intuitive, and the image quality references on which exposure adjustments are based vary between CT vendors (Söderberg and Gunnarsson, 2010; Sookpeng et al., 2014, Merzan et al., 2017). Generally, for ATCM, the attenuation along the patient is determined from the pre-imaging SPRs (one or two directions). The attenuation values averaged over the SPR image are then used as the basis for setting the mA automatically for each rotation to achieve a selected image quality reference using proprietary algorithms (Mayo-Smith et al., 2014). The SPR requirements for ATCM planning vary with CT vendor, and optimum selection for the scanner should be established during commissioning.

(194) In order to operate an ATCM system, a parameter related to image quality must be chosen that can be used as the reference for controlling tube current. The choice of the image quality reference parameter has an important bearing on the operation of ATCM systems, and CT scanner vendors and/or models have slightly different approaches to this.

(195) Noise level can be used as the simplest surrogate for image quality in radiological images (Sookpeng et al., 2014). However, anatomical structures in larger patients tend to have higher contrast due to visceral fat, which facilitates the recognition of organ margins. As a result, a higher level of noise can be tolerated when viewing images of larger patients (Wilting et al., 2001). However, detection of low-contrast lesions (e.g. liver tumours) will require a similar level of noise in thin or obese patients. The image quality references used by ATCM systems can be either a level of image quality for a standard patient, or relate to the noise level in the image depending on the vendor (Martin and Sookpeng, 2016; Merzan et al., 2017).

(196) For scanners in which the operator chooses an image quality reference related to a standard patient, the dimensions from the SPRs are compared with those for the standard patient. The mA is adjusted according to pre-determined levels, with the strength of modulation being chosen by the operator, and the noise level in the image allowed to change moderately with patient size (Stratis et al., 2013; Wood et al., 2015; Söderberg, 2016). For scanners that use a noise index based on the SD as the image quality reference, ATCM systems seek to maintain the same noise level throughout a scan, and a higher noise level may be acceptable for larger patients to take account of differences in contrast between patients of varying size.

(197) As the use of ATCM has developed, the methods used to take account of differences in patient size have varied among vendors. Values of noise index appropriate for patients with varying body mass indices may be incorporated into scanning protocols, and in this case, these should be set up during commissioning.

Alternatively, ATCM may be based on a noise index that uses AI methods to reduce noise and takes account of differences in patient size. It is therefore of utmost importance that users determine how their system operates at installation, and ensure that appropriate settings are put in place during commissioning.

4.4.2. Using automatic tube current modulation and automatic tube voltage selection

(198) Recent scanners have ATVS systems that calculate patient-specific mAs curves for different tube potential levels based on the scan range, patient anatomy, and the contrast required. An optimised tube potential can then be selected for the patient protocol, while the mA is modulated during the scan for that tube potential with ATCM. In recent scanners, automatic adjustments may be made of the tube current when changes are made to the voltage in order to maintain the same patient dose. Therefore, it is important for users to ensure that they understand how tube voltage differences affect dose during operation of their scanner at commissioning.

(199) As ATCM systems from the various vendors use different control parameters, translation of established protocols between scanners of different types is very difficult. Clinical protocols must never be blindly transferred between CT scanners without adjustment, unless the CT scanners are identical models and running identical functional versions of system software. The user can try to set up equivalent protocols by selecting a variable such as CTDI_{vol} (or preferably SSDE) and noise, preferably extending to image texture evaluation and matching, through which to characterise the scanning protocols for patients (or phantoms) of different sizes. The AAPM CT protocols provide vendor- and software-specific examples to use for common clinical indications (AAPM, 2022). Steps for translating ATCM settings in clinical protocols between CT scanners have been described in a number of studies (McKenney et al., 2014; Martin and Sookpeng, 2016; Sookpeng et al., 2017).

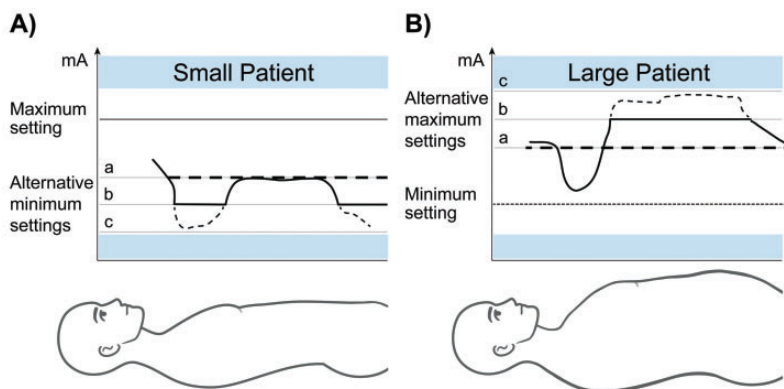


Fig. 4.4. Plots showing examples of the variation in tube current along the bodies of two patients, derived from automatic tube current modulation operation for which noise has been used as a reference. (A) Small patient for whom the minimum mA may have been set: (a) too high, restricting the modulation (bold dashed curve); (b) at an acceptable level (bold solid curve); and (c) too low, allowing the tube current to fall to a level where the image quality may be compromised (fine dashed curve). (B) Large patient for whom the maximum mA setting is: (a) too low, restricting modulation (bold dashed curve); (b) at an acceptable level (bold solid curve); and (c) too high, so mA and dose may rise to an unnecessarily high level (fine dashed curve). Judgements about the maximum and minimum settings that are appropriate should be based on the requirements for image quality. The bands of mA between the shaded areas represent the range over which tube current would be varied if no limits were set. Source: Colin Martin, University of Glasgow, UK.

(200) In certain scanners, limits can be set through the ATCM systems on the maximum and minimum tube currents to avoid the dose level rising too high or image quality being too poor, respectively. In scanners that use an image quality reference related to a standard patient or reference mAs, the limiting mAs values may be set automatically according to patient size. However, for scanner models that use a noise reference, the maximum and minimum mAs settings can be selected by the operator (Fig. 4.4).

(201) Setting of wide limits of tube current may be acceptable for many patients. Example plots showing how the tube current might vary as the scan moves along different patients, and the impact of the limits on tube current are shown in Fig. 4.4. The tube current limits can be set to ensure that doses for small patients are maintained at a high enough level to ensure reasonable image quality (Fig. 4.4A) and doses for large patients are not excessively high (Fig. 4.4B), but if limits are too restrictive, this will curtail ATCM performance. The maximum mA limit can also be set to allow scans to be performed with a small rather than a large focal spot on some scanners in order to achieve better resolution.

(202) The number of photons contributing to an image depends on image slice thickness. Scanners with a reference slice thickness linked to mAs will give a different noise level when the image slice thickness is changed (Sookpeng et al., 2015; Merzan et al.,

2017), but for scanners using an image reference linked to noise, a reduction in the image slice thickness used for acquisition will be accompanied by a corresponding increase in mAs to maintain the same noise level in older scanners (Sookpeng et al., 2015).

4.4.3. Positioning the patient and quality control testing for automatic tube current modulation systems

(203) The projected patient size in AP/PA direction SPR depends on the vertical centring of the patient. If the patient is nearer to the x-ray tube, the SPR image will be magnified, whereas if they are nearer to the detector, the SPR image will be smaller (Matsubara et al., 2009; Supanich, 2013) (Fig. 4.5). Since the ATCM calculations are based on an assumption that the patient is centred within the gantry, tube currents selected by ATCM may be higher or lower if a patient is miscentred. This issue has been addressed through automatic adjustments and centring guidance by some vendors involving, for example, three-dimensional cameras which can also facilitate overall scan preparation and workflow (Zhang and Ayala, 2014; Saltybaeva et al., 2018; Dane et al., 2021; Manava et al., 2023). Some systems allow for small lateral displacements of the table from the console to compensate for patient miscentring. Lateral displacement can create a similar effect, but this does not typically present a problem.

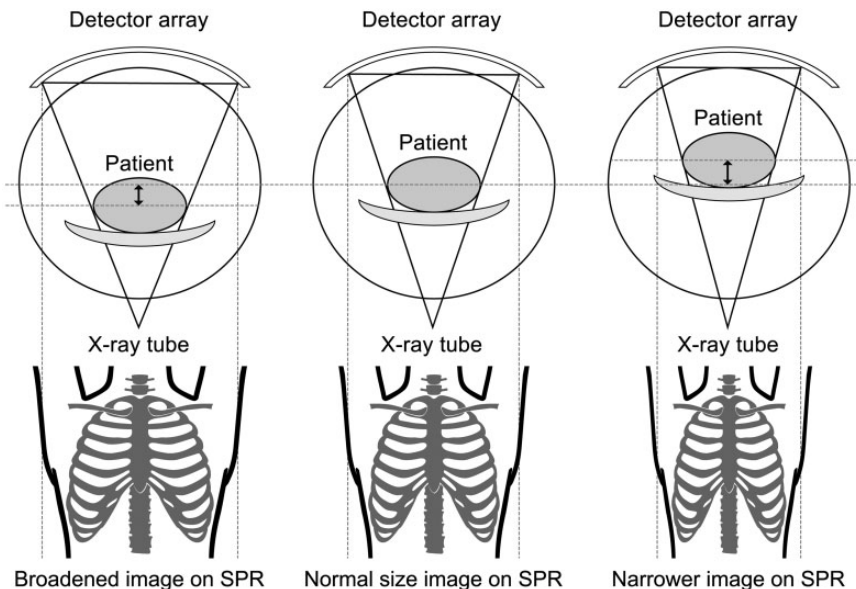


Fig. 4.5. Diagrams showing how the height of the couch can affect the apparent patient dimension on a scan projection radiograph recorded with a postero-anterior projection. When patients are lower (left), the image is magnified, while when they are higher (right), the image is reduced. Source: Colin Martin, University of Glasgow, UK.

The influence of SPR on ATCM and ATVS has been evaluated using phantoms (Kaasalainen et al., 2019) and with patients (Filev et al., 2016).

(204) Testing of ATCM systems should involve phantoms with both discrete and continual changes in phantom diameter and net attenuation (AAPM, 2019b); for example, by using separate phantoms, or with specific ATCM phantoms with combinations of sections (Sookpeng et al., 2013; Wilson et al., 2013; Merzan et al., 2017; Sookpeng et al., 2020). These allow the variation in noise level and tube current with phantom dimension, linked to $CTDI_{vol}$, to be evaluated.

(205) For examinations of the trunk, whenever possible, the arms should be raised above the head to avoid the need for a higher tube current to compensate for the greater attenuation, and to avoid unnecessary exposure of the arms.

4.4.4. Organ dose modulation

(206) Another feature incorporated into new CT scanners is a facility to reduce the mA to the anterior aspect of the body in order to minimise doses to radiosensitive organs such as the breast, thyroid, and lens of the eye. These options, called ‘organ dose modulation’, ‘organ-based tube current modulation’, and ‘organ effective modulation’ by different vendors, reduce tube current typically between 90° and 180° on the anterior aspect where the radiation is incident on the sensitive organs (Kim et al., 2013; Akai et al., 2016; Lambert and Gould, 2016; Kotiaho et al., 2018; Ota et al., 2019; Papadakis and Damilakis, 2020). The tube current in the remainder of the rotation may be increased so that the overall radiation dose ($CTDI_{vol}$) remains constant (Hoang et al., 2012), or an increase in the noise level in the image with a lower dose may be accepted (Dixon et al., 2016). The users should be aware of the organ dose modulation functionality and dose effects of their scanner as there are differences between organ dose modulation methods among different CT vendors.

4.5. Other computed tomography technology and procedures

4.5.1. Dual-energy computed tomography

(207) If simultaneous images can be obtained using different energy spectra, tissues can potentially be characterised or classified based on information about their differences in attenuation (Johnson et al., 2007). The attenuations of materials such as iodine and calcium vary with photon energy in different ways. By modelling the energy dependence of photoelectric and Compton absorption interactions on atomic number, data from dual-energy CT (DECT) can improve performance with a higher iodine CNR, and give the possibility of material-specific images (Fig. 4.6).

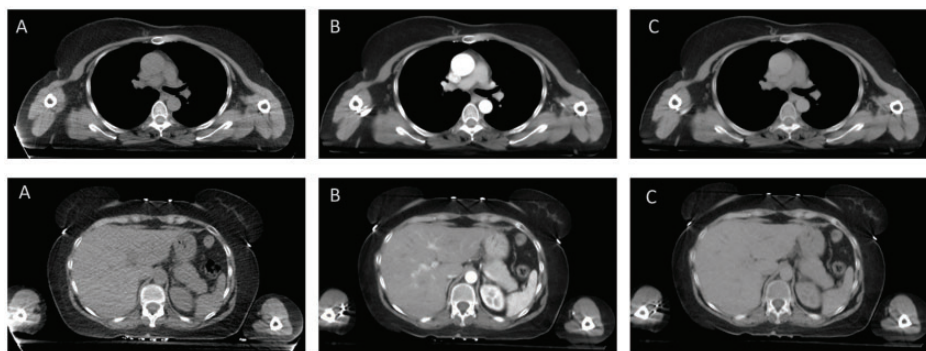


Fig. 4.6. Examples of chest (top) and abdomen (bottom) computed tomography (CT) images derived from unenhanced single-energy CT (SECT) and contrast-enhanced dual-energy CT (DECT) scans. The figures show the following for both patients. (A) Unenhanced images acquired with SECT at 120 kV. (B) Contrast-enhanced virtual monochromatic images (70 keV). (C) Virtual unenhanced monochromatic images (70 keV) available after DECT acquisition. Images courtesy of John Damilakis, University of Crete, Greece.

(208) Five methods are applied to modern CT scanners (incorporating energy integrating detectors) to achieve this ‘spectral energy’ or DECT scanning (Table 4.1) (McCollough et al., 2015; D’Angelo et al., 2019; Borges et al., 2023; McCollough and Rajiah, 2023). Scanners may have two x-ray sources; a single x-ray source with switching of tube potential; a single-source CT with a split beam and different filters; or a single source used with two superimposed detectors.

(209) Where two tube potentials are used in DECT, these are typically 135–150 kV (with additional filtration in dual-source models) and 80–100 kV, and dose levels are similar to those for single-energy CT (Schenzle et al., 2010; Sodickson et al., 2021).

(210) DECT can provide a number of potential improvements for imaging investigations. These include CT angiography with removal of overlying bone which has different energy attenuation characteristics from iodine (Schulz et al., 2012), iodine concentration or effective Z material maps (Sun et al., 2018), and virtual monochromatic (certain keV level) images (AAPM, 2020; Chung et al., 2023). DECT can also enable concentrations of contrast media to be reduced, and there is the possibility of generating a ‘virtual’ non-contrast set of images from a single scan with contrast to avoid a pre-contrast scan, thereby reducing the radiation dose (Fig. 4.6) (Graser et al., 2009; Barrett et al., 2012; George et al., 2017; Rajendran et al., 2021b).

(211) Comparisons suggest that DECT can provide better image quality with comparable or slightly lower doses than conventional CT (Fang et al., 2018). However, the spectral separation remains a challenge, and providing sufficient photon energy differentiation for image reconstruction can be a limiting feature, although various technical solutions are applied in different DECT scanner models. More information on current models, clinical applications, and dosimetric considerations is contained in an AAPM report (McCollough et al., 2020).

(212) As a summary of the image data point-of-view, spectral imaging with dual-energy or spectral detectors offers additional image representations for diagnostics. In order to gain the full potential from spectral imaging, related clinical applications are essential to manage the diagnostic review process and radiologist workload with the increasing CT data sets.

4.5.2. Cardiac and coronary computed tomography

(213) Studies of the heart and coronary arteries have become common, with fan beams extending further along the z-axis and faster acquisition times. There are several ways they can be performed (Montalescot et al., 2013). Depending on the scanner model, the x-ray beam can be run with a single wide-beam axial scan or a continuous helical scan, while the patient is translated through the gantry at a slow speed with a small pitch and images reconstructed retrospectively for one or more phases of the cardiac cycle. More dose-efficient methods set up the scanner prospectively to trigger sequential or faster helical scans at a pre-selected phase of the cardiac cycle determined by the heart rate from the ECG (Husmann et al., 2008; RCR, 2014), and images reconstructed from data combined over multiple cycles or motion-corrected sinogram data. This may require pharmacological support to slow and steady the heart rate, and is more challenging in the infant and young child. X rays at full intensity are only emitted during the phases required for imaging, reducing the dose significantly (Alhailiy et al., 2019). The techniques can provide good image quality at a relatively low dose, mainly for non-obese patients with low and stable heart rates (Achenbach et al., 2010).

Table 4.1. Types of dual-energy computed tomography scanners: advantages and disadvantages

Type	Low kV	High kV	Advantages	Disadvantages
Two x-ray sources 90° or 95° apart	80–100	140–150 (tin filter in recent models to improve spectral separation)	• Simultaneous acquisitions • Tube current and filtration adjusted for each kV • Good spectral separation	• Smaller usable FOV • Possible cross-scatter • Challenging hardware requirements
Single x-ray source with rapid switching of kV using specialised generator	80	135–140	• Good temporal resolution • Shorter spectral delay	• Fast acquisition limits ATCM • More overlap of low and high energy spectra • Challenging hardware requirements
Single x-ray source with switching of kV on alternate rotations	80	130–140	• Low cost • Does not require specialist CT scanner	• Poor temporal resolution • Susceptible to motion misregistration
Single x-ray source that splits beam into two parts with different filtrations and separate detectors in the longitudinal (z) direction	120–140 (gold filter)	120–140 (tin filter)	• Low cost	• Possible cross-scatter and mixture of spectra in centre of beam • Relatively poor temporal resolution • Higher output to compensate for filtration • Lower pitch and longer scan time
Single source with two superimposed scintillation detectors Lower energy component collected with the upper detector	100–120–140	100–120–140	• Good temporal resolution as two data sets collected simultaneously • Good spatial resolution	• More overlap of low and high energy spectra • High attenuation objects reduce lower energy component of spectra • Cross-scatter between detector layers • Challenging hardware requirements

FOV, field-of-view; ATCM, automatic tube current modulation; CT, computed tomography.

(214) The acquisition is usually performed during the diastolic phase to minimise motion artefacts. However, if the pulse rate is >70 beats min^{-1} , end-systolic phase reconstruction may provide a better temporal window to freeze the cardiac movement compared with the diastolic phase (Ruzsics et al., 2009; Hassan et al., 2011). Increasing the length of the scanning time, prior to and after the selected phase of the cardiac cycle being imaged (referred to as ‘padding’), can be used to increase the window for reconstruction, which may be used to improve diagnostic accuracy or to provide a range of cardiac phases for image reconstruction. However, any increase in padding time will increase the radiation dose (Alhailiy et al., 2019).

(215) Cardiac-specific CT scanners are sufficiently wide to encompass the whole cardiac volume in order to image the heart in a single rotation. A review of ECG-gated studies concluded that low tube voltage protocols could reduce doses substantially for smaller patients, while still producing good image quality (Tan et al., 2018). Increases in image noise at lower voltages were offset by the increase in vessel contrast enhancement.

(216) Additional benefits may be obtained from the use of advanced image reconstruction, DL, and related noise reduction. High-resolution photon-counting CT (see Section 4.5.7) can demonstrate coronary artery plaques and stent narrowing with better spatial resolution and fewer artefacts than conventional CT (Rajagopal et al., 2021). Rapid advancement in CT myocardial perfusion imaging allows for: (i) the identification of haemodynamically significant coronary artery disease; (ii) CT delayed-enhancement imaging to detect myocardial scar after myocardial infarction; and (iii) measurement of the extracellular volume fraction in non-ischaemic cardiomyopathy (Ko, 2019). Paediatric heart rates often remain relatively high, despite pharmacological heart rate reduction (Mortensen and Tann, 2018). However, dual-source and wide-beam techniques that allow cardiac scans to be obtained in single sub-second rotations can be used for paediatric patients without the need for sedation. Looking at the overall perspective, the possibility of avoiding sedation with children is extremely valuable, improving the overall clinical process and patient safety.

4.5.3. Computed tomography perfusion studies

(217) CT perfusion involves a series of intermittent CT acquisitions to determine functional haemodynamic parameters such as blood flow, blood volume, mean transit time, and time to peak enhancement (Hoeffner et al., 2004). In addition to cardiac CT perfusion, brain CT perfusion is another primary use, applied for assessment of stroke, but a similar technique may be employed for both brain and body tumour characterisation and assessment of tumour response to treatment, and other inflammatory and vascular conditions. When performing CT perfusion studies, it is essential to keep the tube voltage low (70 or 80 kV) to reduce radiation dose. These CT techniques have provided new insights into the pathophysiology of cancer, stroke, and other diseases such as pulmonary hypertension, and provide quantitative ‘omic’

data. However, examples of skin injury and hair loss from early applications of CT brain perfusion cases in the USA have occurred (ICRP, 2007a). These have involved errors due to the use of incorrect settings by operators who did not understand the potential impact of CT parameter changes on dose.

(218) Procedures with the potential to cause injury should be identified beforehand, and steps taken to ensure that all settings are satisfactory. Checks can be made on skin dose levels, as CTDI_{vol} displayed on the scanner console is similar to the surface skin dose for head scans, while for body CT scans, the surface skin dose is approximately $1.3 \times \text{CTDI}_{\text{vol}}$ (Martin et al., 2017). A ‘CT dose alert’ standard (AAPM, 2011b; NEMA, 2013) introduced an alert function to CT scanners to avoid inappropriately high doses (Mahesh, 2016).

4.5.4. Computed tomography fluoroscopy and guided interventions

(219) CT fluoroscopy is now used to guide interventions combining cross-sectional images or three-dimensional image volumes with almost real-time display. Images at a fixed position are updated continually, providing additional depth information for guiding biopsies and fluid drainage, allowing finer needle control. The technique requires an operator panel for controlling table movement and exposure factors, with exposure usually being activated via a foot-pedal switch.

(220) Tube currents of a few tens of mA are used, giving incident doses of $2\text{--}10 \text{ mGy s}^{-1}$, which are higher than in interventional fluoroscopy. While infrequent, CT interventions may result in relatively high radiation exposures (Arellano et al., 2021). Care is required in monitoring the potential skin dose, as imaging for guidance of a needle, catheter, or probe may be repeated in a similar location (Teeuwisse et al., 2001; Tsalafoutas et al., 2007).

(221) Radiologists or other radiological medical practitioners can potentially receive significant radiation doses to their hands, which will be close to the scan plane during image acquisition as they manipulate biopsy needles. Operator lead screens and aprons are part of appropriate worker protection in CT fluoroscopy, as in interventional radiology settings (Buls et al., 2002; ICRP, 2018b).

4.5.5. Photon-counting computed tomography

(222) Photon-counting CT (PCCT) is a new addition to clinical CT technology with the potential to improve performance in existing CT imaging techniques and provide novel diagnostic applications (Taguchi and Iwanczyk, 2013; Flohr et al., 2020). In contrast to conventional exposure integrating detector (EID) CT, PCCT systems use energy-resolving x-ray detectors that register interactions of individual photons, including the energy deposited. This allows an approximate energy spectrum to be recorded based on energy thresholds, whereas the conventional EID CT technology records the integrated signal intensity from a large number of photons but with a range of energies (Persson et al., 2016; Flohr et al., 2020).

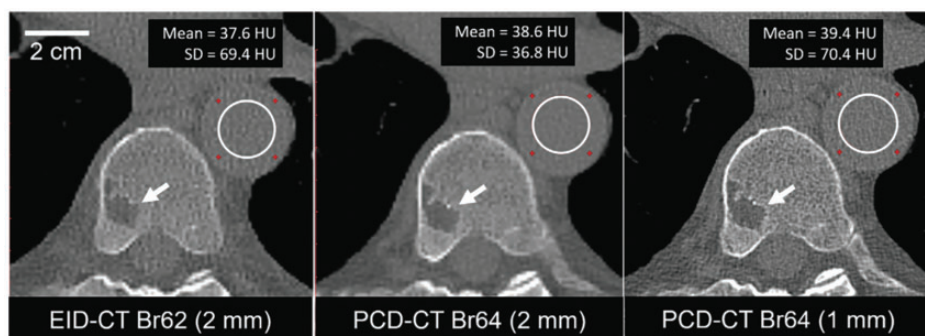


Fig. 4.7. Comparison of images from an exposure integrating detector (EID) computed tomography (CT) scan (left) and a high-resolution photon-counting detector CT (PCD-CT) scan (centre and right) for a 74-year-old male with multiple myeloma, acquired using the same dose (4.2 mGy) and 2-mm slice thickness. The PCD-CT showed 47% lower noise (69.4 HU vs 36.8 HU) in the 2-mm images. Use of a 1-mm PCD-CT slice thickness gave a similar noise level to the EID-CT, and improved delineation of the vertebral lesion (white arrow) (Rajendran et al., 2021b; with permission from the Radiological Society of North America). SD, standard deviation; HU, Hounsfield units.

(223) The potential advantages of PCCT imaging include improved SNR, exclusion of electronic noise, improved spatial resolution, lower patient doses, correction of beam-hardening artefacts, and the ability to distinguish multiple contrast media (Fig. 4.7). This could allow the use of alternative contrast media, and create opportunities for quantitative imaging. PCCT scanners are already in clinical use, and have shown potential for dose reduction in specific scanner designs such as in cardiac and breast imaging (Kalender et al., 2017; Hsieh and Flohr, 2020; Lell and Kachelriess, 2020; Eberhard et al., 2021). PCCT has the potential to change practices in clinical CT imaging dramatically (Rajendran et al., 2021a).

4.6. Development of clinical computed tomography protocols

4.6.1. Establishing clinical protocols

(224) All scans should be performed according to settings agreed and established at the start when a CT scanner is installed and commissioned, and these should be reviewed and revised periodically. The protocols should be developed with input from consultant radiologist(s), lead CT radiographer(s), and the medical physics expert, with recommendations from the company applications specialist. Initial protocols should be set up for examinations that are performed frequently and for the most urgent indications. Values of protocol parameters used more commonly should be set first to lay the basis for subsequent parameter settings. The level of image quality, exposure factors, slice thickness, pitch, filters, and the need for IR or DLIR

should be agreed among the professionals involved (Box 4.3). The optimisation of protocols for paediatric and pregnant patients is considered separately in Sections 5 and 6. AAPM has developed a set of protocols for specified diagnostic tasks that can be accessed via the internet (AAPM, 2022), and these can provide a useful starting point.

Box 4.3. Factors to be aware of when setting up computed tomography scan protocols and scanning patients

Pitch, mA, slice thickness and rotation time

- Be aware of interactions between different parameter settings on your scanner; for example, how automatic tube current modulation (ATCM) is affected by changes in primary reconstruction slice thickness and reconstruction kernel.
- Compare results of new protocols with original protocols when making any changes. It is recommended that a database with separated files recording the historical changes in the protocols is maintained [acquisition and reconstruction parameters for each clinical protocol and for each computed tomography (CT) system in the hospital, which should be updated regularly]. These can be handy when major changes or upgrades in systems take place and CT protocols need to be reinstalled.
- Know whether or not the tube current remains the same or is varied automatically when pitch is altered.
- Volumetric acquisition mode using thin slices increases the image noise, but allows for multi-planar reformats review at thicker reconstruction and three-dimensional visualisations. Thin slices benefit from reduced contrast averaging by the partial volume effect.
- Poisson statistics of image data acquisition: when acquisition slice thickness (or radiation dose) is halved, the noise will increase by a factor of $\sqrt{2}$. Note that the relationship with dose is not certain with more advanced reconstruction methods [iterative reconstruction (IR) and deep learning image reconstruction (DLIR)].
- Proportionate reductions in patient dose can be achieved by reducing tube current, while being careful not to compromise diagnostic information.
- Techniques that increase scan time (lowering pitch, decreasing total collimation width, or increasing rotation time) may be problematic in certain contrast-enhanced CT scans that involve rapid biokinetic changes or chest imaging with the need for breath hold.

Tube potential (see Box 4.2)

- A lower tube potential can improve contrast for smaller patients, and may reduce dose with appropriate choice of mAs.

- When imaging structures are enhanced with contrast media, the iodine contrast-to-noise ratio can be used as an approximate image quality metric for evaluating adjustments to tube potential and mAs.
- Automatic tube voltage selection (ATVS) systems calculate patient-specific mA curves for different tube potential levels to allow an optimised tube potential to be selected.

Patient set up and plan

- Ensure that the patient is centred in the gantry before commencing an examination, as this may affect operation of ATCM and ATVS.
- Use appropriate anatomical guidelines to define scan start and stop positions to ensure consistency.

IR or DLIR techniques

- IR and DLIR are not themselves dose-saving techniques, but their use can enable exposure factors to be reduced through improvements in image quality.
- The dose reduction that can be achieved with IR or DLIR will depend on the clinical task. Substantial dose reduction may be possible for imaging high-contrast objects.
- Vendors offer options with different strengths or levels of IR or DLIR, giving more or less noise reduction. Determine which are appropriate for each application.
- More aggressive noise reduction may be beneficial for detection of low-contrast structures, but application of too high a strength may affect tissue texture and visualisation of low-contrast lesions.
- IR or DLIR strategies that improve spatial resolution or decrease artefacts, rather than reduce noise, may be beneficial for CT angiography.
- Measurements of the noise power spectra from phantoms can be helpful for interpreting changes in the visual appearance of images generated with alternative reconstruction methods.

(225) Protocol optimisation should be based on consistent CT scan protocol naming and coding. Thus, the organisation with multiple CT sites may implement harmonised imaging protocols which can be identified unequivocally based on the protocol name and code. Some vendors have developed protocol management features into their software tools, which enable protocol data from scanners to be pulled for centralised review and comparison, protocol version handling, and even distribution of revised protocols to interoperable scanner models. This will greatly assist successful protocol management in larger, multi-site organisations.

(226) Optimisation of any radiological x-ray modality should be based on the proper limitation of exposure range to the area based on clinical indication and the correctly defined FOV. The level of image quality required should be agreed among

the professionals involved. Some of the factors and relationships that should be considered when setting up protocols are summarised in Boxes 4.3 and 4.4.

(227) Input is required from all radiologists and other radiological medical practitioners to determine image quality requirements (Maués et al., 2018). There should be consensus amongst radiological medical practitioners within a department with regard to the clinical protocols for each application. Different dose protocols for individual radiologists are not justified, and can lead to errors and unnecessary dose variation. The aim should be to create a single standard examination protocol suitable for the clinical task. This could be feasible, with the lead radiologist for each organ/body part being the person-in-charge of the corresponding organ-area-specific protocols and collaborating with the other radiologists, radiological medical practitioners, radiographers, and medical physicists involved. Ideally, there are ongoing interactions with the clinical referrers (e.g. specialty conferences) and managers to optimise protocols, and communication with patients and their families to improve health literacy.

Box 4.4. Points to be considered when setting up protocols (assumes use of automatic tube current modulation)

Setting up protocols for computed tomography (CT) procedures is a crucial part of optimisation, and some of the points to be considered during this process are summarised here.

- The choice of proper clinical image quality reference for specific indications is the primary determinant of the dose to the patient.
- Understanding how automatic tube current modulation (ATCM) works with respect to the particular vendor for the CT scanner is key to achieving proper operation and avoiding potential errors.
- Do not choose an mAs image quality reference that is too high or a noise reference that is too low for operation of ATCM.
- Establish a standard routine for performing the scan projection radiograph linked to ATCM (and automatic tube voltage selection) operation, following vendor recommendations to ensure that the image signal is adequate.
- For scanners that use an image noise reference, the operator may need to select a higher noise level for larger patients to avoid high patient doses.
- Ensure that settings of maximum and minimum current, where they are determined by the operator, are appropriate and do not unintentionally restrict mA modulation.
- Scanning phantoms in the form of cones or sections with different dimensions provide a useful method for quality control, understanding, and monitoring of the ATCM operation. Anthropomorphic phantoms can be an alternative.
- Organ dose modulation reduces tube current for angles where x rays are incident on sensitive organs (mainly eye, thyroid, and breast).

(228) Whether or not a scan with contrast is required will depend on the clinical questions to be answered. Some patients will only require a single scan (particularly children), but others will require several scans with pre-enhancement and post-enhancement during the arterial or venous phases. The possibility of using DECT, if available, should be borne in mind, as this can produce virtual non-contrast images without extra phases. Timing of the contrast bolus by using bolus tracking or applying a test bolus will also be important for obtaining satisfactory images.

(229) Exposure factors should be individualised through use of ATCM and ATVS to adjust dose for patient size, although it may be necessary to have separate technique charts or protocols for particular patient cohorts [e.g. such as different age groups (preferably by size in terms of diameter) for paediatric patients, and for small, average, large, and obese patients] (Box 4.2). As different clinical questions require different diagnostic approaches, there should be a sufficient number of indication-specific CT scan protocols established, easily available, and properly maintained in order to have a more efficient and comprehensive optimisation process in CT. Overall optimisation of CT scan protocols should be managed in a larger context by integrating this action into daily clinical routine. In multi-site and multi-scanner organisations, certain anatomical or organ range protocols could be managed by that organ-specific radiology team in order to agree and make adjustments to achieve consistent image quality target levels for similar indications. Thus, the number of indication-specific protocols should reflect the true need for separate protocols in that organ range, and these protocols should be kept under coherent control. Likewise, the local or vendor-specific expert teams (including radiographers, medical physicists, radiologists, and vendor application specialists) may ensure that the multiple protocols covering many organ ranges and indications are consistently maintained to reflect the current capabilities of the scanner models and local patient flow process.

(230) Agreement in setting the initial protocols is just the start of this process. The practice should then be benchmarked through dose surveys and assessments of image quality during the early stages of implementation, and regularly by QA activities and audits during normal clinical use. For more information about the explicit CT protocol setting, web resources for protocol data are available from professional medical organisations and medical physicist organisations (e.g. AAPM, 2022; CTisus, 2022).

4.6.2. Patient dose audit

(231) Insufficient feedback on dose (and image quality) tracking may lead to a dose increase over time or leave doses at a high level in order to ensure that image quality is good, despite the potential of reduction using the available CT system tools. CTDI_{vol} gives a measurement of dose within a phantom of standard size (Box 4.1), and is suitable for dose surveys and optimisation of practices. However, it is a poor reflection of doses to individual patients of varying size, and does not represent

real morphology and anatomy; SSDE has been developed to provide more information on doses to individual patients (Box 4.1). Where dose information is contained in the DICOM header and RDSR for each examination, audits of patient doses are becoming easier to perform (Annex B) (ICRP, 2023). Commercial dose management systems or functionalities integrated into PACS/RIS software provide access to substantial amounts of data; these systems provide an overview of the doses associated with particular examinations to be obtained more easily, as well as allowing comparisons between different CT scanners (Tsalafoutas et al., 2023). Recent systems also cover other relevant features of optimisation, such as scan protocol and scanner utilisation management features.

(232) Median values of dose quantities derived from survey data can be compared with DRLs (ICRP, 2017, 2023). The form in which data are presented – for example, using boxplots or bar charts to compare results with regional or national DRLs – can assist local staff in understanding the level of optimisation that has been achieved.

(233) If local median values are higher than the DRLs, the protocols, techniques, and image quality should be reviewed. There are many possible reasons why median values of dose quantities may be higher or lower than the DRL. First of all, the calibration of the values displayed in the scanner should be checked to see if they are realistic. Next, the clinical imaging task for which the DRL value has been established should be similar to the one being studied, with similar patient cohorts and patient weight ranges. Finally, a check should be made as to whether DLP and $CTDI_{vol}$ are both high, as this can be informative in determining possible causes.

Table 4.2. Possible causes of higher doses for trouble shooting dose audit results

Observed effects	Patient size	Things to check and possible causes
$CTDI_{vol}$ acceptable, but DLP appears too high	Average	Check whether scan length is reasonable or multiple scan series are included
$CTDI_{vol}$ acceptable, but total accumulated DLP appears too high	Average	Check number of scan phases with and without contrast being performed, and whether the number is reasonable
$CTDI_{vol}$ and DLP both high	Average	Review all major scan parameters, including, for example, kV, mAs (or ATCM) level
$CTDI_{vol}$ and DLP both high for body scan	Small	Is the displayed $CTDI_{vol}$ for a small field of view that for a head phantom rather than a body phantom?
$CTDI_{vol}$ and DLP both high	Average or large	Is too low a noise level or too high an ATCM image quality reference being selected?
No tube current modulation effects observed	Large or small	Check whether tube currents set for ATCM are appropriate, the maximum value for a large patient or the minimum for a small patient. Also, check the modulation curves displayed, if they are available

$CTDI_{vol}$, volume averaged computed tomography dose index; DLP, dose length product; ATCM, automatic tube current modulation.

It should be noted that, even if doses are lower than the DRL, this does not mean that further optimisation is not possible or should not be undertaken.

(234) The following paragraphs discuss possible causes of higher doses, and Table 4.2 summarises some of the possible causes linked to whether $CTDI_{vol}$ and/or DLP are high. An estimation of these parameters is usually available on the screen before a scan is performed, and can potentially enable a quick check of parameters to be made at this stage. If radiographers are familiar with the range of appropriate values, they can modify a protocol to avoid delivery of an unnecessarily high dose to the patient. Whatever changes might be made, it is pivotal to ensure that the image quality remains adequate for the clinical task.

(235) If DLP is high but $CTDI_{vol}$ is within the normal range, the scanned region may be longer than necessary. Another common reason for higher values for DLP is the use of more scan series, as scans may be performed initially without contrast medium, followed by scans enhanced with contrast. If this is the case, consideration should be given to whether these series are all necessary for the clinical task being undertaken. It should be noted that DRL values apply to a single CT scan series and not to the cumulated DLP of the entire examination.

(236) If both DLP and $CTDI_{vol}$ are high, the scan parameters should be reviewed in detail to determine if they were justified or corrective actions need to be taken. The ways in which controls influence patient dose and image quality for CT scanner models from the various vendors are different, so it is important that members of the core radiological team understand how the settings on the scanner affect the imaging process (ICRU, 2012; AAPM, 2014).

(237) There may also be reasons why the $CTDI_{vol}$ value displayed may not be appropriate. For paediatric patients in particular, it is necessary to check that the $CTDI_{vol}$ value is the appropriate value for the body (referenced to 32-cm diameter PMMA cylindrical phantom), as if a small FOV has been selected, the $CTDI_{vol}$ value may relate to a head scan (referenced to 16-cm diameter PMMA phantom) for which the corresponding dose value is approximately double (Box 4.1). For some older scanners operating under ATCM when systems were first introduced, the maximum value of $CTDI_{vol}$ is displayed rather than the average or effective value over a whole scan, which will again give overestimated results for the analysis.

(238) Assessment of doses for patients of standard weight is often insufficient for a full assessment of scanners operating under ATCM, as there may be particular issues for scans of large or small patients, so it is informative to view the form of the distribution for all patients. If patient size information is available, ideally measured from the scanner display, dose quantities $CTDI_{vol}$, DLP, and, optimally, SSDE can be plotted against patient diameter (Sookpeng et al., 2014; ICRP, 2017; Kanal et al., 2017; Boos et al., 2018; ACR/DIR, 2022). Various steps involving more demanding analysis techniques are provided by medical physicists or engineers. The proper use and configuration of dose management systems require dosimetry and statistical knowledge in order to exploit their full potential in clinical use. When configuring and implementing dose management systems, it is important to verify that DICOM

and RDSR are activated and in use whenever possible (Annex B), as these structured reports provide an extensive description of radiation exposures for individual irradiation events. Also, the validation of dose data provided to the dose management system should be verified when new equipment is linked up or updated. Continual improvement is a general quality management principle which is included in the international quality standards.

(239) There are many occasions where routine optimisation actions should be supplemented by more sophisticated physical dose and image quality assessments. Dose monitoring results occasionally trigger questions where answers are not provided by simple evaluation of exposure parameters. In such assessments, standard dose measurements related to CTDI formalism can be supplemented by studies on anthropomorphic phantoms which, in many cases, may give much more realistic dosimetry references for patient-specific dose calculations and even allow for more advanced image quality assessment. Anthropomorphic phantoms may be used in physical or computational form. In physical form, actual point-dose measurements can be made in relevant radiosensitive organ locations in the phantom to verify the dose performance of the scanners with actual clinical protocols. Some phantoms also allow for the insertion of ionisation chambers. Computational phantoms may be used in more elaborate dose simulations to acquire organ dose estimates and three-dimensional dose distributions. An example of such Monte Carlo dose simulation,

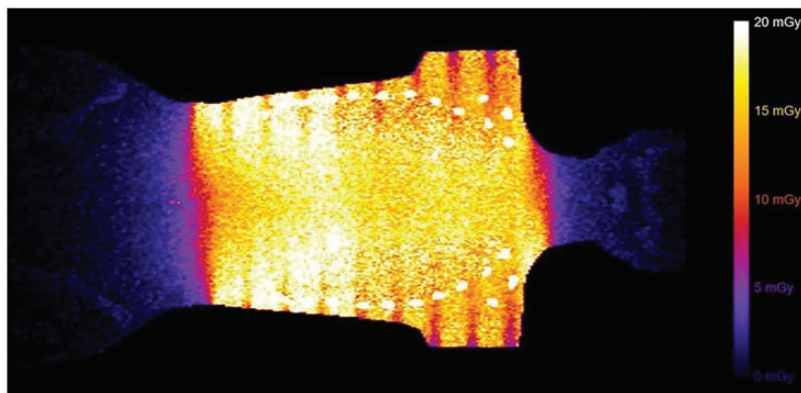


Fig. 4.8. Example of highly heterogeneous three-dimensional dose distribution at a coronal view resulting from a helical chest computed tomography (CT) scan performed on an anthropomorphic adult female model. Brighter colours refer to higher absorbed doses in that specific position. Note the scattered radiation which extends outside the primary scanned region. The stripe patterns indicate the helical beam path during the scan. Dose has been calculated with Monte Carlo simulation, taking into account the CT scanner x-ray source model and scan parameters. The colour bar dose scale has been chosen to represent a typical and quite conservative dose level, and does not demonstrate more modern low-dose settings that are available on new equipment. Image courtesy of Mika Kortensniemi, HUS Diagnostic Centre, New Children's Hospital, Finland.

providing a three-dimensional ‘heat’ map of dose levels, is presented in Fig. 4.8. This also shows the periodic variation in dose across the skin surface.

(240) The benefits of anthropomorphic phantoms are that the whole scatter environment provided by the human body can be included in the scan scenarios and dose assessments. Physical and computational anthropomorphic phantoms may also be used for image quality evaluations. Thus, dose and image quality characteristics may be studied in reference objects. Such actions link the optimisation process to scientific research. Further information about patient-specific dosimetry is provided in the joint AAPM-EFOMP TG246 report (AAPM, 2019a), where this subject is discussed extensively with valuable reference data for medical physicists.

Box 4.5. Guidance for computed tomography protocol development and maintenance

- Standard clinical protocols should be agreed by the core team and communicated within each facility.
- There should be sufficient indication-specific computed tomography protocols available and maintained to provide an efficient and comprehensive optimisation imaging process.
- The process of protocol optimisation should involve evaluation of clinical image quality and technical measurements of image quality in phantoms as a part of regular quality assurance.
- Analysis of dose performance in scans of phantoms performed in parallel can be useful, together with measurements of noise, limiting resolution and contrast visualisation.
- Changes to protocols should be made in stages, with checks made to confirm that the desired changes have been achieved, and a dose audit performed at an early stage.
- Protocol development should be a continuing process with measurements being made of the impact of changes, and the whole process repeated.
- Radiologists, other radiological medical practitioners, radiographers, and medical physicists should all feed into protocol development; other stakeholders (referring clinicians and vendor application specialists) may also add information to the local optimisation process.

4.6.3. Subjective and continuous assessment of computed tomography protocols: the core team and beyond

(241) Once established, the scan protocols should be reviewed periodically, and changes should be implemented as required. Protocol development should be a continuing process, with measurements being made of the impact of changes and the whole process repeated. When changes are made to clinical protocols, this should be discussed with all those involved. The new protocol should be tested against the old protocol prior to use in patients, and depending on the magnitude of the

changes, practical assessments on phantoms or simulations may be required to evaluate changes in dose and image quality. Guidance on the approach to practical optimisation is given in Box 4.5.

(242) Changes such as the introduction of IR or DLIR, or reductions in dose levels should be made in stages. Shortly after implementation, checks should be made to confirm that the desired changes have been achieved, and evaluations should be carried out to ensure that all radiologists and other radiological medical practitioners interpreting the images find the changes acceptable. Next, a dose audit should be performed. The previously mentioned protocol management software and tools are currently emerging from different vendors in addition to the dose management software, which should make consistent indication-specific protocol optimisation, version management, and updates easier for CT users. These automated methods are even more important when protocol management is pursued in larger multi-site organisations with larger numbers of scanners and established indication-specific CT scan protocols. General arrangements for optimisation that relate to facilities at different levels in development of their optimisation strategy are set out in Box 4.6.

Box 4.6. Optimisation arrangements at different levels of development

C: Basic

- Requests for computed tomography (CT) scans include reason for referral and clinical history of patient.
- CT radiographers trained by vendor applications specialists have received equivalent training by staff at the facility through a robust competency/proficiency programme.
- Clinical protocols agreed for imaging of all key body regions.
- Separate paediatric protocols based on patient age (head) or body weight (trunk).
- Standard anatomical references used to set scan limits.
- Automatic tube current modulation (ATCM) settings provide appropriate modulation for patients of all sizes.
- Basic tube voltage selection based on indication, patient size, and use of contrast.
- Reconstruction filters specified for common types of examination in use.
- If available, iterative reconstruction (IR) or deep-learning-based image reconstruction or restoration (DLIR) implemented for selected procedures with adjustment of exposure factors, after agreement with radiologists.
- Acknowledgement of dose display and using diagnostic reference levels (DRLs) (published or national) at least for the most general examinations (head, chest, abdomen).
- Regular (daily tube warm-up and air calibration) constancy checks performed by radiographers quality control (QC).
- CT scanner QC tests to characterise scanner performance carried out regularly, at least annually.

B: Intermediate

- Comprehensive scan protocols available for a wide range of clinical indications encountered regularly and agreed by all radiologists and other radiological medical practitioners.
- Protocols agreed for scanners throughout facility based on similar criteria.
- Consistent nomenclature and naming of indication-based protocols throughout facility.
- System in place for regular review of protocols by core team.
- Protocols include adjustment in tube potential according to patient size (with or without contrast), and appropriate mAs values chosen based on contrast-to-noise ratio evaluation.
- Protocols optimised through careful choice of exposure factors.
- Utilisation of specific scanner features for improved optimisation and patient safety.
- ATCM settings specified based on patients' clinical conditions and sizes.
- ATCM and automatic tube voltage selection set up based on image quality references agreed with radiologists based on review of clinical images.

- Minimal use of multiple pass scanning through same body part, unless necessary for specific clinical indications.
- IR or DLIR used for the majority of examinations with reduction in exposure derived from evaluation of the quality of resulting images.
- Regular monitoring of doses and comparison of the doses with the DRLs.

A: Advanced

- Use of advanced technology and software for optimisation including IR or DLIR, dual-energy CT and, most recently, photon-counting CT.
- Unified guidelines for indication-specific scan protocols throughout organisation.
- Separate paediatric protocols based on clinical indications and patient age (head) or body weight/thickness (trunk).
- Consistent nomenclature and naming of indication-based protocols throughout organisation.
- Agreed system in place for revision of protocols, possibly with the lead radiologist for each organ/body part being the person-in-charge and collaborating with the other radiologists, other radiological medical practitioners, radiographers, and medical physicists involved.
- Harmonised scan parameter settings for all CT scanners of similar type, and uniformity of performance between different scanners in multi-scanner and multi-site organisations.
- Process in place for continual review and assessment of protocols taking account of feedback on clinical image quality and dose survey results.
- Utilisation of organisation-wide dose and protocol management systems in order to provide continual data for monitoring and improvements, evaluation of safety events, and near-misses.
- Utilisation of anthropomorphic phantoms and/or simulation models to perform more extensive dose and image quality evaluations on scanner protocols for optimisation and research.
- Utilisation of model observers and other methods (e.g. artificial-intelligence-based algorithms) for clinically relevant image quality assessments.
- Communication with radiological community to share best practices (up-to-date protocols) and with the public to communicate benefit/risk information.

5. PAEDIATRIC PROCEDURES

(243) Key points in this section:

- Children are not small adults – the radiological professionals (the core team of radiographers, radiologists, and medical physicists) must have adequate education and training in optimisation of imaging for infants and children.
- Paediatric protocol optimisation requires an understanding of the clinical indication, patient size, ability of the patient to cooperate, and alternative examinations available locally to answer the clinical question.
- Adopting a layered approach, the next step is education of the referring clinicians and patients/families, followed by the managers, regulatory agencies, and other stakeholder groups, to enable an integrated system in which understanding of the complex processes involved is improved continuously.
- Referrers, children, their parents, and carers should be involved in shared decision-making throughout the process of considering, performing, and reviewing imaging examinations. Education and advocacy improve both radiological protection and health literacy.
- Monitor collimation as part of the QA programme in digital radiography to ensure that radiographers collimate radiographic exposures properly, rather than cropping images after the exposure.
- A grid is usually unnecessary for radiography or fluoroscopy of infants and children under the age of 3–4 years, and may not be required for chest imaging of older children.
- Patient age is a poor substitute for thickness in determining exposure requirements. As with any projection radiograph, body part thickness is the most important determinant for the technique. The abdomens of the largest 3-year-olds are the same size as the abdomens of the smallest 18-year-olds. Use of weight is a better alternative to age that can be measured relatively easily.
- Use dose reduction methods when practicable with fluoroscopy, including virtual collimation, removal of the grid, additional copper filtration, LIH, and reducing pulse rates during pulsed fluoroscopy to the lowest setting that provides adequate temporal resolution in the image.
- The optimisation core team (radiographer, medical physicist, and radiologist) should share bi-directional learning with other clinicians, families, and other stakeholders. They should review imaging protocols periodically to implement best practices.

5.1. Requirements for imaging paediatric patients

(244) This section will consider improvements in radiological protection, and safe and effective imaging care of infants and children. There are specific requirements relating to optimisation of imaging for paediatric patients, and optimisation strategies (the process of selection). Part of improving the radiological protection and the

imaging outcomes for children is raising awareness of issues through education and inclusion of all stakeholders: the patient (when appropriate), parents, carers, radiographers, paediatric clinicians, medical physicists, and nurses in this process (Fig. 5.1).

Dissemination of Knowledge for Radiological Protection of Children

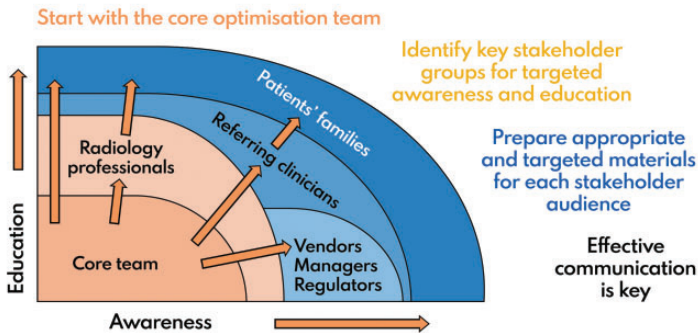


Fig. 5.1. An example of expanded inclusiveness in optimisation education to all stakeholders. This begins with education and awareness of the core optimisation team, followed by radiology professionals; referring clinicians; facility managers, regulators, and vendors; and, finally, patients and families. Each layer builds a larger and expanding volume of educated and aware participants in the process of imaging care. Source: Colin Martin, University of Glasgow, UK.

(245) Less than 10% of healthcare resources are spent on children, so much of the focus and medical training is on adult care (Bui et al., 2017). This fact sometimes makes it difficult to gain the attention of healthcare systems, health professionals, and the equipment manufacturers to ensure that there is adequate education, training, and optimisation of imaging for children, and, most especially, for infants (defined as age <1 year). The default policies, procedures, imaging protocols, and manufacturer equipment settings are all typically set for adults and these can – and do – lead to unnecessary irradiation, inappropriate or non-diagnostic imaging procedures, and paediatric patient harm if there are false positives, false negatives, or test complications. One size does not fit all for paediatric optimisation (Fig. 5.2). Paediatric protocol optimisation requires an understanding of the clinical indication, patient size, ability of the patient to cooperate, and alternative examinations available locally to answer the clinical question.

(246) The term ‘optimisation’ requires a broader definition than has been applied in the past (Fig. 1.1), and a layered approach (Fig. 5.1) that begins with the medical physicist, radiologist, and radiographer core team. ICRP has provided guidance on setting DRLs for ionising radiation imaging for children (ICRP, 2017), and some paediatric DRLs are being set (EU, 2018; Kanal et al., 2022). The setting of a DRL is a starting point – but only that – to identify opportunities for improvement.

It should be followed by re-audit and continual re-assessment (ICRP, 2023). DRLs are derived from the third quartiles of patient dose distributions, but comparison with median values from national dose distributions can be an additional tool for improving optimisation (ICRP, 2017). The core imaging team should engage in ongoing interaction with all stakeholders involved in the imaging processes, with continuous learning to improve optimisation and outcomes. These interactions include the patients, workers (e.g. nurses), and family members and carers who often hold the children to enable the imaging to be successful.



Fig. 5.2. An example of visual social media messaging from Image Gently. ‘The Message: simple, direct, clear, and resonant’. One size does not fit all for optimisation (with permission from Image Gently).

5.1.1. Why ‘children are not small adults’

(247) On average, infants and children have higher radiation sensitivity compared with adults. Many of their organs are more sensitive to radiation than those in adults, although other tissues have similar radiosensitivities (UNSCEAR, 2013). There is now clear evidence of an association between CT scans of children and the induction of malignancies (de Basea Gomez, 2023). Moreover, the longer life expectancy in children allows more time for any harmful effects of radiation to manifest, and provides another rationale for special consideration for imaging children.

(248) It is important to understand the unique considerations and approaches when imaging children for setting the scene, before moving to the specific requirements relating to optimisation of imaging for paediatric patients. If the saying is old and well trodden that ‘children are not small adults’, there is a good reason for saying it again. It is easy to see that patient size varies in the paediatric world much

more than in the adult world, with differences by a factor of >200 (from premature babies of 300–400 g to obese adolescents >100 kg body weight) (EU, 2018). However, not that long ago, there were no differences in CT protocols for children and adults except at specialised childrens' hospitals (Donnelly et al., 2001). These 'one size fits all' CT protocols used by community hospital imaging facilities were one component that resulted in unnecessary radiation doses to children.

(249) However, there are other reasons why children require more attention before, during, and after their imaging care (<https://www.imagegently.org>). One important consideration is an understanding of paediatric medicine that requires proper selection of the imaging for an infant/child who may not cooperate but cannot be sedated. The pathology in children is different from that of adults, so the clinical protocols differ in basic ways; when children have cancers, these are often large masses that grow quickly, not subtle or tiny carcinomas as often seen in adults, and this enables imaging protocols that have lower mAs values to be used, and – in addition – the radiologist interpreters may tolerate more image noise. Further, children have congenital anomalies and infections more frequently than adults. When recurrent imaging of the same body part is required, planned use of fewer images, more collimated radiographs and fluoroscopy, or CT with noisier images that can be acquired with lower radiation doses should be considered. When imaging is requested, other considerations must include whether sedation or anaesthesia will be needed in the infant or younger child. If the smaller child can undergo imaging (e.g. ultrasound) without sedation, it is safer, less costly, and sometimes faster for all. Medical and radiological professionals must have adequate initial education and a continuing commitment to training in radiological protection to care for infants and children (Vassileva et al., 2022). Surveys by national and regional radiography organisations indicate that there is often inadequate paediatric training and wide variations in digital paediatric radiological practices (Morrison et al., 2011; McFadden et al., 2018; Alsleem et al., 2019; Foster and Clark, 2019).

(250) Radiological professionals (the core team of radiographers, radiologists, and medical physicists) must have adequate education and training in optimisation of imaging for infants and children. Adopting a layered approach, the next step is education of the referring clinicians and patients/families, followed by the managers, regulatory agencies, and other stakeholder groups to enable an integrated system in which understanding of the complex processes involved is improved continuously. In order to be successful, the imaging facility must gain the trust of the child and the parents or carers, as a child will not cooperate unless he/she feels safe. Therefore, the use of distractors (toys) and a nurse or childcare specialist to calm the child and family while undertaking the imaging procedure can make all the difference between success and failure.

(251) A culture of safety and of radiological protection is often present in paediatric healthcare facilities (Malik et al., 2020). To obtain this level of awareness, radiology workers require education and training in how to work with children and families. When working in a medical imaging facility, ICRP has recommended

minimum acceptable levels of radiological protection education and ongoing training for all types of workers (ICRP, 2009). When working with infants and children and their families, further education, awareness, and ongoing training may be helpful. The following sections focus on several clinical, medical physics, and practical considerations that are known to improve paediatric imaging outcomes.

5.1.2. Preparing the child and family

(252) There is no more overlooked quality factor in paediatric radiology than to have an experienced and patient radiographer when preparing the child and family or caregiver. Inadequate or unsuccessful imaging occurs in facilities that do not image children regularly or do not invest in training staff to learn about caring for children. The facility should provide a child-friendly environment that includes warm colours, decorations, furniture for children, toys, and distractions in the imaging rooms, and the provision of a childcare specialist if possible. These specialists may use a mock imaging room to introduce the child and family to equipment and a procedure beforehand (<https://www.radiologyinfo.org>). Online resources for the referring clinician, the radiologist, and the patient and family about preparing the patient are available in English and Spanish on international (WHO, 2016; ACR/RSNA, 2020; ESR, 2020; IAEA, 2020) and regional radiological protection campaign websites. Some provide podcasts describing what to expect from their imaging procedures from a child's viewpoint.

(253) When children are imaged, parents have long pushed for a culture of safety and transparency, ensuring that the child and their family are an integral part of the care team. This has become a concept called 'shared decision-making' that is a key component of patient-centred health care. It is a process in which physicians and patients work together to make decisions and select imaging tests, treatments, and care plans based on clinical evidence that balances risks and expected outcomes with patient preferences and values (HealthIT, 2013). Referrers, children, their parents, and carers should be involved in shared decision-making throughout the process of considering, performing, and reviewing imaging examinations. Education through web and written literature improves both radiological protection and health literacy.

(254) Parents, families, and health professionals have worked together over time to provide imaging facilities that are safe and have a welcoming environment for children. For example, the workers use language that is easily understood and invites the patient/family to participate, and they use the patient's/parents' language (via a translator). In addition, all imaging professionals should be prepared to answer the child's or parents' questions, or to direct them to an appropriate colleague to respond to concerns raised. A parent or carer is often present in the imaging room to hold the child, so that they remain still during imaging and to comfort them. This decreases anxiety and the chance that repeat radiation exposures will be required.

(255) Many imaging facilities have developed written decision aids or direct parents to websites that provide information that helps them understand why

their child is undergoing an imaging procedure, how to prepare for it, and what to ask about, as well as a description of possible benefits and risks, alternatives to the procedure, and the next steps for the patient and family (ACR/RSNA, 2020; ICRPædia, 2024; Image Gently, 2024). In order to put risks into context, an approximate value for the effective dose from a chest x ray on a child is between 0.01 mSv and 0.1 mSv, equivalent to between 1 and 10 days of exposure to natural background radiation (Wall et al., 2011; Image Gently, 2022a).

(256) To prevent unnecessary radiation exposures and repeat procedures, a time investment – on the one hand, educating the referring physicians; and on the other hand, explaining to the child and family about the imaging procedures – is crucial. Additionally, in the long term, such actions save a significant amount of anxiety, stress, and tears on the part of all involved in the process.

5.1.3. The adolescent and pregnancy status

(257) An assessment is required for female, trans, and non-binary adolescents (age 12–18 years) of the possibility of pregnancy prior to a procedure involving exposure of the abdomen (Badawy et al., 2023). These groups are particularly vulnerable to social and/or parental pressures that can potentially result in the patient providing misinformation about their reproductive status. The imaging facility's standard adult policy for documentation of the last menstrual period date and verbal and/or written screening for pregnancy status may therefore not be sufficient. Staff may question adolescents separately from their parents, and many facilities require a pregnancy test if there is any doubt about possible pregnancy. In some countries, imaging facilities may have policies that require all female and, increasingly, trans and non-binary adolescent patients to undergo urine pregnancy testing, unless they are known to be pregnant. The imaging procedures for which precautions are required include: abdominal-pelvic CT, angiography, and other FGI procedures in the pelvic area under fluoroscopy. Additional procedures to consider include radiography of the abdomen, pelvis, hips, and lumbosacral spine (ACR/SPR, 2018).

5.1.4. Patient positioning and immobilisation

(258) Proper patient positioning is key to a successful imaging procedure and is often overlooked when the infant or child is not cooperative. In these circumstances, measures should be taken to ensure that the patient is immobilised during imaging. With appropriate consent, an immobilisation device may be used, or a parent/worker can hold the patient to prevent them from moving. This will allow the beam to be centred correctly with the proper projection and collimation needed. In the past, any shielding would be placed at this time, but this routine practice is, for the most part, no longer considered appropriate (Section 2.3.4), and more efficient optimisation methods should be implemented.

(259) Immobilisation is required for many children when performing radiographic studies. Devices that are approved by the local facility, such as sponges, plexiglass, or sandbags, may be used in infants or for small body parts (fingers, hands, wrists, toes). Immobilisation devices for supine or upright chest and supine abdominal radiographs are available for infants. When the child needs to be held during a radiographic exposure, the parent or carer would usually be asked to do this unless they are pregnant. No part of the body of the parent/carer should be in the radiation field of the exposed radiographs, fluoroscopy, or CT examinations; a QA process for procedures may be helpful for peer education. Radiographers and other facility workers (nurses) may also help to immobilise a child; however, this would be regarded as an occupational exposure, and care should be taken to ensure that no individual is exposed to scatter radiation repeatedly. Lead personal protective equipment must be used by staff and carers who provide assistance. Portable radiography in particular should have a QA programme for attention to positioning, collimation, artefacts, and variation in dose parameters for repeated chest and abdominal radiography in the neonatal intensive care unit. For more educational materials, the reader is referred to Image Gently (2022e).

5.1.5. The critical importance of collimation in children

(260) Collimation matters more in limiting unnecessary radiation dose to infants and children than in adults. Collimation should be performed prior to radiation exposures. However, it continues to be a commonly performed task after exposure in children, leading to overexposures (Temsah et al., 2021). If a chest radiograph on a neonate (age <1 month) is not collimated properly, it is likely to include radiosensitive organs both above (thyroid, red marrow in the skull, lens of the eye) and below (stomach, colon) the area imaged. When an upper gastrointestinal procedure is performed on a neonate and does not use adequate collimation, unnecessary exposure is given to radiosensitive breast tissue above the region imaged, and the pelvis and ovaries below. When an abdominal helical CT scan is performed on a child, more than the required body part may be irradiated because of over-ranging (Section 4.2.2), which may expose the female breast and more of the pelvis. Portable radiography should have a QA programme to monitor collimation which can be a particular issue (Fig. 2.3).

(261) Collimation should be monitored as part of the QA programme in the digital radiography environment to ensure that radiographers collimate radiographic exposures properly, rather than cropping images after the exposure (Section 2.3.2). A survey by the American Society of Radiologic Technologists showed that 50% of radiographers used postprocessing to collimate their radiographs in 75% of their cases (Morrison et al., 2011), and this practice continues in many facilities. The use of electronic collimation after exposure during postprocessing increases doses to patients and may not be evident in the PACS or the medical record. The need to

collimate must be stressed during radiographer training. Assessment of competency and periodic review training using a doll or a phantom may be helpful.

5.2. Adjustments in image quality requirements and dose with patient size

(262) The clinical indications in children differ greatly from adults, and depend on the age, time of year (infection prevalence), and regional genetic and environmental factors. However, there are trade-offs in image quality and dose with smaller body parts and/or thinner CT acquisitions in that image noise will increase. Good radiographic, fluoroscopic, and CT technique includes attention to patient positioning, field size, and collimation; optimisation of exposure factors; use of pulsed fluoroscopy; limiting fluoroscopy time; and consideration of whether a grid should be used.

(263) The acceptable level of image noise for answering a clinical question is a key determinant of the exposure level required in digital radiology. A higher level of noise is often acceptable for paediatric imaging in facilities where images are interpreted by trained paediatric radiologists, as compared with radiologists dealing predominantly with adult imaging. The most important factor is that the interpreting clinician can obtain the clinical information required.

(264) Use of a grid in radiography or fluoroscopy is usually unnecessary for infants and children aged <3 years (or <12 cm in AP diameter) (Kleinman et al., 2010). In addition, parts of the body >12 cm thick with structures containing air (such as the chest) can be imaged without a grid. In these cases, there is a trade-off between image quality and dose, as a higher mA and/or longer exposure time are required if a grid is used. When a higher contrast image at a well-managed dose is desired during interventional procedures, the use of copper filtration (see below) with a grid is useful. Grids should be chosen taking account of patient size (grid ratios of 2:1 to 6:1 for small size to at least 10:1, and preferably 12:1, for chest radiographs), and used with 100–130 cm SID (Image Gently, 2022a).

(265) Reducing pulse rate during pulsed fluoroscopy to the lowest setting that still provides acceptable temporal resolution substantially reduces the patient's radiation dose below that of continuous fluoroscopy settings (Box 3.2). Experienced practitioners use 7.5 or fewer frames per second for routine general fluoroscopy, but interventional cases require faster rates for cine acquisition mode; higher frame rates are often used for video modified barium swallow studies.

(266) The insertion of additional copper filtration in the x-ray beam is an effective method of reducing IAK at the patient while delivering IAK to the image receptor necessary to provide the desired image quality (see Section 2.2.2 and Box 2.3). While 0.2 mm of copper reduces the patient air kerma more than 0.1 mm of copper, trade-offs exist, as the 0.2-mm filter reduces contrast in the image more than the 0.1-mm filter. As more x-ray photons are attenuated in the 0.2-mm filter, more photons must be generated, which requires a greater tube voltage, tube current, and/or exposure time. Increasing the voltage may reduce the contrast, while increasing the exposure

time may result in more motion unsharpness, and increasing the tube current may result in a switch from the small to the large focal spot size, also resulting in reduced image sharpness. As the size of the paediatric patient increases, the choice of 0.2 mm of copper may sacrifice too much image quality for a limited reduction in patient dose.

(267) The default setting for imaging equipment set by vendors is for adult imaging, and must be reset for infants and children. Key provisions include the techniques mentioned above, as well as the development of paediatric-specific protocols for common clinical conditions [see, for example, a sample technique chart for paediatric abdominal radiography, Slide 53 of 66, Keith Strauss (Image Gently, 2022a)]. There is a need for more standardised, specific CT paediatric protocols to be developed that can be made available to all centres undertaking paediatric exposures for common conditions, with four to five weight categories for body CT imaging, and three to four age categories for head CT imaging (ICRP, 2017; IAEA, 2020; AAPM, 2022; Almén et al., 2022; ACR/AAPM/ASR, 2023; Image Gently, 2023).

5.3. Radiography

5.3.1. Choice of exposure factors and exposure levels

(268) Large surveys show that 74–85% of all ionising radiation imaging procedures in children are radiographs (UNSCEAR, 2000, 2008; Dorfman et al., 2011; NCRP, 2019b). The general operation and approach to optimisation for radiography is considered in detail in Section 2, but there are specific issues that relate to paediatric imaging. Digital radiographs use postprocessing to adjust for over- and underexposures, with 43% of paediatric radiographs being overexposed (Don, 2004; Don et al., 2021; Temsah et al., 2021). Some modern equipment provides icons for small, medium, and large patient sizes, but the paediatric sizes may not be included. It is vital to ensure that the exposure settings used are not higher than necessary. The Image Gently campaign ‘Back to Basics’ can be used as a mnemonic to evaluate image quality. First, there are 10 steps to understanding and applying the basics of the digital imaging environment in paediatrics.

- **Understand the basics of digital imaging:** Digital radiography has several advantages over traditional screen film radiography (see Section 2). It has a latitude of exposure that is approximately 100 times greater, reducing the number of repeat examinations due to underexposure and overexposure. Image manipulation (processing) is possible to change the appearance of the image, thereby making subtle characteristics in the image more apparent. The electronic images can be stored and distributed anywhere within a healthcare system, providing access to the images within minutes after exposure. While the spatial resolution (sharpness) of the digital image is less than an image on film, the superior contrast and other improvements in image quality, including image processing available only in the digital image, result in superior clinical studies with digital radiography.

- **Understand the challenges associated with digital imaging:** Digital radiography is fundamentally different from film/screen, and exposure creep can lead to over-exposures (see Section 2.2.3) (Gibson and Davidson, 2012). Differences in image acquisition processes and terminology have led to confusion in understanding techniques. Inadequate initial education and ongoing training in the radiology community about these issues have exacerbated problems with the use of digital radiography for children.
- **Learn exposure terminology:** The radiologist and radiographer should become familiar with technique and exposure factors used for common paediatric examinations. Not only tube potential, mAs, and added beam filtration, but EI, EI_T, and DI, which are discussed in Section 2.2.3. EI, DI, and, ideally, KAP values should be present on the displayed image (Willis and Slovis, 2004). The image processing organ programme (e.g. portable chest, abdomen, hand) should also be displayed. These data provide feedback to the radiologist, and can help in solving problems when an image is not acceptable. When the values are not displayed, the vendor should be consulted to ensure that members of the imaging team can identify the values within the DICOM metadata.
- **Establish manual technique charts using a team approach:** The team includes the radiographer, radiologist, medical physicist, and vendor. This may be particularly important for infants and small children. The AEC sensors commonly used in adults are often problematic in children if the body part is smaller than the set of AEC sensors (Goske et al., 2011). In some cases, AEC may be used on children if only the central sensor is activated, and the child is positioned so that the body part covers the entire single sensor completely. However, for infants and smaller children, the imaged area of anatomy may be smaller than the single sensor, and then manual techniques are required. Focused exposure charts are important for key common examinations such as chest, abdomen, and small body parts.
- **Measure body part thickness or child's weight:** X-ray absorption/transmission depends on the composition of the body part being imaged, and the body part thickness is the most important determinant for the technique. Patient age is a poor substitute for thickness, as the abdomens of the largest 3-year-olds may be similar sizes to those of the smallest 18-year-olds (Kleinman et al., 2010). Therefore, patient age cannot be used reliably as a guide for techniques. Reverting to 'Back to Basics' by measuring patients with callipers will ensure that a standardised technique is selected. However, if this is impractical, weight should be used in selecting the exposure factors. Knowing the body part and its thickness, one can set the appropriate tube potential, filtration, and mAs for the examination. Automated evaluation of patient thickness based on the exposure factors used and a knowledge of the characteristics of the x-ray detector may also be an option (Worrall et al., 2020). The goal is for reproducible, consistent images for children with body parts of similar sizes.
- **Use grids only when body thickness is >10–12 cm:** The main purpose of anti-scatter grids is to remove scatter from the image to improve the subject contrast in the

image. Scatter starts to degrade subject contrast in the image significantly when the body part is $>10\text{--}12\text{ cm}$ of water-equivalent thickness. Structures that are $>12\text{ cm}$ thickness containing air, especially chest radiographs, can be imaged successfully without a grid. The use of grids should be minimised in children with bodies less than $10\text{--}12\text{ cm}$ thick (Carlton et al., 2019). Depending on the grid selected, anti-scatter grids double or triple the exposure factors necessary to obtain an adequate image. When a grid is required, grid ratios of eight and line numbers of 40 lines cm^{-1} (moving grid) are usually sufficient, even at higher tube potentials.

- **Collimate prior to the exposure:** With the advent of digital radiography, it is possible to open the collimators, then manipulate and electronically crop the image after the exposure. Radiologists may not be aware that cropping is widely used (see Section 2.3.2), yet radiologists are responsible for the image before cropping occurs. The cropped portions of the body are exposed to unnecessary radiation. While opening the collimators may be necessary occasionally for inclusion of anatomy such as an arm in a percutaneously inserted central venous catheter, under most circumstances, it is better to immobilise the patient and collimate appropriately before the exposure, rather than crop the image later.
- The benefits of collimation prior to exposure are reducing the area exposed, lowering the patient dose and KAP, and minimising scattered radiation and thus improving image quality (Curry et al., 1990). In addition, a well-collimated field will exclude extraneous structures outside the area of interest, such as shields, that might affect the applied image processing. Wide open collimators may affect the EI, giving a false indication of the exposure.
- **Use of additional filtration:** In the paediatric patient, total radiation dose should be managed carefully to provide image quality appropriate to the type of clinical examination. While reducing the radiation dose is a desired objective, this cannot be at the expense of appropriate image quality. Not all generators (particularly mobile radiography units) are capable of delivering the short exposure times that are required for these higher tube potential techniques. Consequently, lower tube voltages are often used for paediatric patients, and these result in higher patient doses. The insertion of additional filtration will reduce the IAK rate and allow delivery of lower doses with higher tube voltages within the range of exposure times available on such equipment. The benefit of copper filtration is discussed in Box 2.3 and Section 2.2.2.
- Rare-earth filter materials with absorption edges at specific wavelengths have little or no advantage over simple inexpensive aluminium-copper filters. All tubes used for paediatric patients in stationary, mobile, or fluoroscopic equipment should have the facility for adding additional filtration, and for changing it easily when appropriate. Usually, up to 1 mm of aluminium plus 0.1 or 0.2 mm of copper as additional filtration is adequate. For standard radiographic voltages, each 0.1 mm of copper reduces output by about the same as 3 mm of aluminium, but removes a higher proportion of the photons between 20 and 40 keV (ICRP, 2013b).

- **Accept the noise level appropriate to the clinical question:** Radiologists prefer images that have little noise (Don, 2004; ACR/AAPM/SIIM/SPR, 2022), but noise intolerance can lead to exposure creep. To avoid this, radiologists need to become familiar with and monitor the EI values for their equipment, and understand the relationship between exposure indicators and the visual appearance of noise in an image (Section 2.2.3). Exposure creep can be avoided through routine QA monitoring of the DI and the level of image noise.
- Experienced paediatric radiologists may be tolerant of more noise in some body tissues than in others. For example, noise does not affect the visualisation of high-resolution structures, such as bone detail, or the endotracheal tube or chest tube (Don, 2004), while the ability to identify disease processes such as surfactant deficiency disease/respiratory distress syndrome of the premature newborn and low-contrast structures is more noise sensitive (Roehrig et al., 1997). As users become more comfortable with the technique/noise relationship with digital radiography, lower-dose follow-up studies that are tailored to answer a specific question, such as checks on positioning after adjusting line placement, may become more common.
- **Have a comprehensive QA programme:** It is critical that radiologists, radiographers, and medical physicists (the core team) develop standards for their imaging facility through the QA programme (ICRP, 2023). In addition, regional and national DRLs are being developed for common imaging procedures, although provision of paediatric DRLs lags behind that for adults. The European Union published paediatric DRLs in 2018, including paediatric abdomen, chest, skull, and pelvis radiography DRLs for several age or weight categories (ICRP, 2017; EU, 2018, Table 10.2a).

5.3.2. The Image Gently ‘Back to Basics’ tool for evaluation of image quality

(269) The word ‘BASICS’ is a mnemonic tool to help operators to remember aspects that must be considered when taking a radiograph: beam, artefacts, shielding, immobilisation and indicators, collimation, and structures.

- **Beam:** Is the anatomy centred in the beam? Is the tube angled correctly?
- **Artefacts:** Are there any external artefacts that are obstructing the beam?
- **Shielding:** Gonadal shielding is no longer considered appropriate for routine x-ray imaging as the protection it provides from scatter is minimal (see Section 2.3.4; AAPM, 2019c; Hiles et al., 2020, 2021). If the family requests shielding because it was used previously, the reason for the change in practice should be explained to the family, but shielding may be used with the family sharing in the decision-making.
- **Immobilisation:** Could immobilisation help to reduce the chance of a repeat exposure? Should the facility seek immobilisation advice and training from a paediatric imaging centre?

- Indicators: What does the EI mean and how can adjustments be made for similar patients undergoing the same examination? Is the DI appropriate? (see Section 2.2.3 and Table 2.2)
- Collimation: Only expose the patient to the necessary amount of radiation. Never leave collimators open and rely on post-exposure, electronic collimation, as this will give the patient additional exposure.
- Structures: Check if the necessary anatomy or device is demonstrated properly.

5.3.3. Imaging of neonates (age ≤ 1 month) and infants (age ≤ 1 year)

(270) The small focal spot of a bifocal x-ray tube (nominal focal spot sizes of 0.6 and 1.2 mm typically) should be used for neonates, infants, and children. This choice includes any examination using 100 cm SID and no grid. As the patient size increases, the large focal spot should be selected when the maximum rated tube current for the small focal spot and a 20-ms exposure do not provide enough mAs to expose the image receptor properly. Exposure times >20 ms with the small focal spot on larger children should be avoided to prevent motion unsharpness in the image. When SID is >100 cm, use of the large focal spot is necessary, even for smaller patients, to avoid the need for exposure times >20 ms (ICRP, 2013b).

(271) When infants need radiography, this may be performed with portable radiographic units, and immobilisation may be necessary. The ‘Back to Basics’ steps for image optimisation are important (Section 5.3.2). Manual technique charts are often required for optimisation.

(272) Consider how an AP chest radiograph of a neonate, AP thickness 6 cm, compares with that of a large adult with a PA thickness of 30 cm. The HVL of soft tissue (the amount of tissue that will decrease the air kerma by half) is approximately 3 cm at 70 kV for imaging equipment with standard filtration. The difference in thickness of eight HVLs requires a reduction in mAs by a factor of 256. Thus, a typical neonatal (portable) chest x ray with a digital radiography detector might be performed with 70 kV and 1 mAs.

(273) The Image Gently campaign has a safety checklist for radiographers performing portable radiographs on children (Image Gently, 2022c) that can also be used for adults (see Box 2.4).

5.4. Fluoroscopic imaging

(274) While the use of fluoroscopy in adults has decreased markedly over the past decades with the increase in cross-sectional imaging and other endoscopic procedures, general gastrointestinal and genitourinary fluoroscopy continue to be performed routinely and valued in infants and children. The general operation and approach to optimisation is considered in detail in Section 3, but it is critical to understand the justification and optimisation of common procedures in the paediatric community. When considering the use of fluoroscopy in a child, in addition to

optimisation of technique, a further question is whether alternative imaging procedures such as ultrasound could be used.

(275) Careful selection of equipment that provides the required image quality at properly managed radiation dose levels for children is important. In the clinical practice of paediatric fluoroscopy, fewer x-ray photons should be needed to create the images required for diagnosis compared with adult fluoroscopy, providing opportunities for reducing doses in infants and smaller children. Whereas the ESAK rate for an abdominal examination on a large teenage patient may be 90 mGy min^{-1} , that for a neonate may be only 1 mGy min^{-1} in a properly configured machine. The equipment should have the capability to facilitate dose reduction strategies. Effective doses from a fluoroscopic examination on a child that might be $0.45\text{--}0.59 \text{ mSv}$ with continuous mode fluoroscopy might be only $0.05\text{--}0.07 \text{ mSv}$ if the procedure were fully optimised (Image Gently, 2022b), so there is a need for operators to understand and use all the facilities available.

(276) While barium or iodinated contrast media are administered at room temperature in adults, there is more use of contrast warmers for infants and young children. The use is not to reduce the likelihood of vascular extravasation, but to avoid the risk of body temperature decrease or even shock from contrast infusions into the gastrointestinal or genitourinary systems (Kok et al., 2014).

(277) A team approach to QA for dose management and image quality in paediatric fluoroscopy should be developed with the radiologist, radiographer, and medical physicist (Ward et al., 2008; ICRP, 2018a; Image Gently, 2022b). The development of paediatric DRLs will aid optimisation. While, to date, few paediatric DRLs have been published for general fluoroscopy, a few publications provide important information. A recent publication (Somasundaram et al., 2022) allows any site, paediatric or adult, to estimate exposure levels as a function of patient thickness at the 75th percentile for examinations conducted at their site in the operating room with mobile C-arm units, or the four general paediatric examinations performed in radiology of gastrointestinal, voiding cystourethrogram, video swallow, or tube placement, provided that the site can determine the average exposure level for a handful of patients of the most common size imaged for each type of study. The European paediatric DRLs include a DRL for micturating cystourethrogram for four age levels (EU, 2018, Table 10.2a). An example of self-assessment in dose management and quality improvement for micturating cystourethrogram/voiding cystourethrography paediatric fluoroscopy is available on the Society for Pediatrics Radiology website (SPR, 2008).

(278) Staff will be exposed to scattered radiation during fluoroscopy procedures, and the radiological protection principles of time, distance, and appropriate shielding should be applied (ICRP, 2018b). The scatter dose rate from patients is lower in the paediatric environment as patients are smaller, but more use of magnification may be needed, and require the operator to move nearer to the patient to immobilise or position the patient properly.

(279) When performing fluoroscopy, a parent and/or carer may be welcomed into the room to help calm the child, and sometimes hold the child during the procedure. Care must be taken to check that radiation dose management is performed for these individuals as well as for the patient, the radiographer, and the operator. Is everyone shielded properly? Are the hands holding the child out of the FOV? Is the patient positioned properly to start the fluoroscopy? The large size of the II and typical noises of the fluoroscopic unit can be scary for young children, so cooperation can be a challenge. Preparation and teamwork are key.

5.4.1. Techniques for the fluoroscopy operator to consider

(280) There are a number of dose reduction methods to consider prior to commencement of a fluoroscopic procedure on a child. These include the use of virtual collimation, low attenuation table tops, removal of the grid, copper filtration in addition to aluminium, use of the LIH option, avoidance of magnification mode with IIs when possible, and the use of pulsed fluoroscopy on the lowest pulse rate setting that provides adequate temporal resolution. If possible, any dose reduction feature of the fluoroscopy unit should be set as the automatic default value at the beginning of an examination. The operator can quickly make changes to the controls if the image quality is not adequate. This avoids the use of patient dose rates higher than necessary, based on settings used for the previous patient.

(281) The selected pulse rate for pulsed fluoroscopy should be the lowest that provides the operator with adequate temporal resolution, which is determined by operator experience, image quality of the equipment available, and type of procedure being performed. This setting may be as low as 1–2, 2–4, or 10–15 pulses s^{-1} , respectively, for placement of a peripherally inserted central catheter, voiding cystourethrography or gastrointestinal studies, or video swallow studies. The pulse rate can be changed by the operator during a procedure depending on the clinical task. The use of the LIH feature allows time for the operator to review the image, collimate, or move the fluoroscopy image receptor, and also allows the image to be stored. If higher quality images are required for storage and review, the dose is increased by a factor of 10. However, these exposures may be justified to convince the clinician or surgeon of the diagnosis or to confirm a subtle abnormality or both. Optimisation is not always about lowering the dose; it is about obtaining the image quality necessary to answer the clinical question(s).

(282) During fluoroscopy with a mobile C-arm, the patient should remain as far from the x-ray tube (at least 30 cm) and as close to the FP detector or II as is comfortable to reduce dose. When a tilt table is used with adjustable SID, the tower holding the image receptor should be positioned as close to the exit plane of the patient as is comfortable to reduce dose to the patient. If the distance of the focal spot to the table top is adjustable (under table x-ray units), the maximum allowed distance should be used for children to reduce patient dose.

5.4.2. Equipment features for dose reduction

(283) Filtration. Assuming that aluminium filtration is used, the minimum tube potential should be 70 kV for infants, and range up to 100 kV for large children. The tube current usually ranges from 0.5 mA to 6 mA depending on the patient size (Image Gently, 2022b). When a 0.1–0.2-mm-thick copper filter is inserted in the beam, the tube potential for infants can be lowered to 55 kV. However, use of smaller thicknesses of copper may not alter the image quality and, therefore, no change in the exposure factors is needed (Image Gently, 2022b).

(284) ADRC. ADRC (or ABC) maintains the dose rate at an acceptable level through adjustment of the exposure parameters (Box 3.3). Fluoroscopic patient entrance dose rates are normally limited to between 80 and 100 mGymin⁻¹. In Europe it is limited to 100 mGymin⁻¹ and in the USA the limit is set at 88 mGymin⁻¹ (10 Rmin⁻¹). However, where there are relatively large areas containing positive contrast medium (e.g. full bladders), ADRC should be switched off to avoid excessive dose rates (ICRP, 2013b).

(285) Patient dose should be recorded with all information made available from the fluoroscopic equipment (KAP or P_{KA} , $K_{a,r}$, see Annex A and fluoroscopy time) with the understanding that displayed values of P_{KA} or $K_{a,r}$ on the fluoroscopy unit may have errors of $\pm 30\%$ (Lin et al., 2015). The parameters relating to dose are more important, but fluoroscopy time can be compared between operators performing similar procedures in the review of operator technique, if KAP is not available.

(286) Anti-scatter grids. Grids increase dose to the patient and may not be necessary for children with thicknesses <12 cm (Box 2.2).

(287) Use of copper filtration. While most modern fluoroscopic and radiographic equipment used for paediatric examinations has added copper filtration, some units may not. Most tubes in x-ray equipment have a minimum inherent filtration of 2.5 mm of aluminium. Additional filters can further reduce the unproductive radiation and thus patient dose (ICRP, 2013b). However, while a unit may have the ability to insert additional copper filtration into the x-ray beam, this may not be the default setting out of the factory. A configuration change at the imaging facility may be necessary to utilise the additional filtration.

5.4.3. Portable fluoroscopy

(288) C-arm (portable) units for intra-operative use are typically configured for adult patients, and this may result in higher doses to paediatric patients and higher scatter radiation to the operator than necessary during paediatric imaging. Mini C-arm units are approved by the US Food and Drug Administration for orthopaedic fluoroscopy of extremities, but are unfortunately sometimes used for other applications in infants and children. C-arm units configured for paediatric imaging should be considered for use at child-based facilities.

(289) When C-arm equipment is used, it is important to be aware of the proximity of the skin to the x-ray source in lateral and oblique views, as it may be closer than in

the PA view and give patients high skin doses. The source to skin distance should be maximised by moving the table up away from the x-ray tube when the C-arm has been positioned. A separator cone can be applied to ensure a minimum 30 cm separation between the patient and the tube. Operators should be aware that oblique tube geometry means that the x-ray beam traverses a ‘thicker’ section of the patient and will increase the fluoroscopic dose rate. When the C-arm is put in the lateral position, the patient should be at a similar distance from the source to that permitted for the PA view. Field overlap in different runs should be minimised (ICRP, 2013b).

5.4.4. Fluoroscopically guided interventions

(290) The complexity of FGIs, especially in infants and young children, requires specific training in paediatric interventional procedures and safety. Sedation or anaesthesia are required for many procedures, and when contrast media and other medications are used, their volume must be monitored carefully (there have been reports of hypothyroidism after iodinated contrast in some neonates). Major paediatric interventional procedures should only be performed by experienced paediatric interventional radiologists due to their complexity.

(291) Optimisation and training for interventional procedures may include simulation with a doll or anthropomorphic phantoms, and a pre-procedure checklist (Image Gently, 2022c). Substantial radiation dose reduction can be achieved by reducing the pulse rate. Cardiac procedures may require up to 30 pps to capture the rapid beat of the paediatric heart, while most other interventional paediatric procedures can use pulse rates as low as 3.75 or 7.5 pps (ICRP, 2013b; Image Gently, 2022b). Limitations on patient entrance dose rates are not applied when using cine mode. Therefore, for safety reasons, it is suggested that cine mode should be turned off when imaging infants and children unless required for interventional procedures.

(292) Use of equipment that provides small focal spots. For example, an x-ray tube with three focal spots (0.3, 0.6, and 1 mm), typically found in neuroangiographic suites, provides better high-contrast resolution than the standard dual focal spot tube with a typical 0.5 mm small focal spot.

(293) Further, multi-modality imaging in the interventional imaging suite may allow use of ultrasound, especially in smaller children, and two-dimensional tomography instead of CT.

5.5. Multi-detector computed tomography procedures

(294) There are large variations in the use of CT, and the techniques and dose levels delivered across the world, which make optimisation important, especially for paediatric examinations (Smith-Bindman et al., 2019). Special attention to the principles of justification, optimisation, and a team approach to a radiation dose management and image quality programme are essential in paediatric medicine, with the core team being extended to include the CT equipment vendors (Fig. 5.1).

(295) Adjustment of exposure parameters to suit the specific application, clinical need, and information required should always be considered. An example where a low dose technique was adequate is shown in Fig. 5.3.

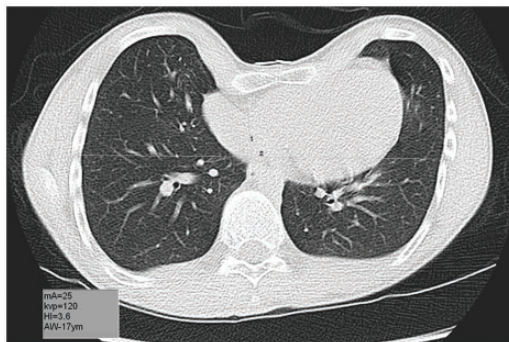


Fig. 5.3. Single image from a limited, low dose chest computed tomography pre-surgery for pectus excavatum in a 17-year-old boy. The dose is low, but would be less with newer equipment and a lower tube potential. Technique: 120 kV; 12.5 mAs; rotation time 0.5 s; volume averaged computed tomography dose index 0.63 mGy; dose length product 11.2 mGy cm. The measured Haller Index was 3.6 (severe). Source: K. Applegate, Department of Radiology, University of Kentucky, USA (retired).

(296) Advances in CT technology have created new opportunities for clinical uses in children with marked dose reduction and increased speed in image acquisition. These include IR and DLIR methods (Section 4.3) (Nagayama et al., 2021), photon-counting CT (Section 4.5.5), and hybrid functional imaging capabilities (CT/PET, CT/SPECT). Sample paediatric protocols of the head, chest, and abdomen with pelvis for each of the major vendors and their commonly available CT models are available on the AAPM website (AAPM, 2022). The European Union paediatric imaging project produced DRLs for four age groups for head CT, and five weight categories for chest and abdominal CT (EU, 2018, Table 10.2b) and other evaluations of DRLs have since been published (Kanal et al., 2022).

(297) DECT, spectral CT (Gottumukkala et al., 2019; Tabari et al., 2020), and photon-counting CT can enable lower patient doses to be achieved (see Section 4.5.1). Protocols may be built using less contrast media, ATCM, and iterative post-processing to correct for contrast agent and metal artefacts. Other potential applications include imaging of children who have devices that preclude the use of MRI, vascular imaging, and use of virtual non-contrast body or neuro-imaging to assess for stones or acute haemorrhage (Siegel and Ramirez-Giraldo, 2019; Tabari et al., 2020) so that a single pass through a body part is sufficient.

(298) Keeping the dose low is important, but it is secondary to treatment of the patient, and sometimes there is a need to increase the mAs to identify particular features and accomplish the clinical task (Fig. 5.4).

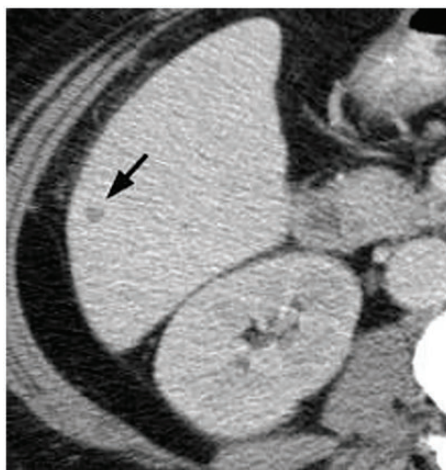


Fig. 5.4. Example of an immunocompromised child with leukaemia and possible candidiasis. The protocol uses an mAs 20% higher than the standard to visualise a single low density lesion in the liver (arrow). Source: K. Applegate, Department of Radiology, University of Kentucky, USA (retired).

Box 5.1 Questions for the core optimisation team to ask and statements to consider when planning a computed tomography scan of a child

- Have you considered alternative imaging such as ultrasound or magnetic resonance imaging?
- If a computed tomography (CT) procedure is selected, adjust the dose by choosing the tube potential and tube current appropriate for the size of the child (three to four age categories are suggested for the head, and four to five weight categories are suggested for the trunk) (ICRP, 2017). The tube potential and mAs can often be lowered from the pre-set values.
- Use the scan projection radiograph, which is an antero-posterior or postero-anterior (and sometimes lateral) projection image (Section 4.2.2), to select the start and stop positions for the CT examination. Scan only the indicated area of the body (do not over-range).
- Ensure that the influence of the scan projection radiograph on operation of the automatic tube current modulation is understood, which will require investigation by a medical physicist (Section 4.4).
- As a general rule, only scan once through the body part; pre- and post-contrast phase scans. Delayed scans rarely add any information but do increase the radiation dose (Rostad et al., 2018). However, there are certain indications when multiple scans will be required, such as for stroke and liver tumour imaging.

(299) There is scope for optimising CT and developing low and ultra-low dose CT protocols. Some can be used on paediatric patients for specific indications such as pectus excavatum CT (Fig 5.3) and sinus CT pre-surgery. There is an Image Gently basic 10-step guide to optimisation for paediatric CT (Strauss et al., 2010). A set of simple questions to ask and statements to consider when planning a CT scan and developing a protocol are given in Box 5.1 (WHO, 2016; ICRP, 2017; ESR, 2020; IAEA, 2020; Image Gently, 2022d).

(300) Some of the important aspects that should be considered in order to achieve successful CT scans of children are listed in Box 5.2.

Box 5.2. Important aspects to consider for the successful computed tomography imaging of children

- The need to prepare patients and their families (as noted above for fluoroscopy).
- Understanding why computed tomography protocols differ from those for adults; it is not just about dose (see Section 5.1.2).
- The possible need for immobilisation or sedation/anaesthesia.
- Factors governing the choice of exposure parameters.
- Use of automatic tube current modulation with paediatric patients.
- Challenges in use of automatic tube voltage selection in children.
- Use of post-processing with iterative reconstruction and/or other techniques.
- Audits of paediatric patients and implementation of diagnostic reference levels (ICRP, 2017, 2023).
- Methods for dealing with differences in patient size in dose audit to obtain usable data, such as use of size-specific dose estimates (Box 4.1) (AAPM, 2011a, 2014).
- Use of a patient dose monitoring system that tracks dose (Smith-Bindmann et al., 2019; ACR/DIR, 2022).
- Reference to quality assurance and dose management programme resources that are available for guidance (Strauss et al., 2010; ICRP, 2017, 2023; ACR/DIR, 2022; Image Gently, 2022d).

(301) With the rapid acquisition time of CT imaging, the use of sedation or anaesthesia in children or infants is relatively uncommon. It is recommended that short acquisition times are used whenever possible, after checking that the reduction in the number of projections does not compromise the quality of the clinical information. Exceptions include infants aged >3 months (that cannot be swaddled) and children up to age 4 years that require intravenous contrast media, and those paediatric patients who cannot be calmed through normal comforting by childcare specialists and/or distractors (see Section 5.1.2). There are also procedures requiring

very narrow collimation, such as temporal bone head CT, that may require sedation/anaesthesia. Simulation with phantoms may be useful in making assessments.

(302) Newer equipment includes safety features in terms of safety alerts to reduce protocol errors, although each facility must set levels and create their own protocols. The AAPM ‘Recommendations regarding notification and alert values for CT scanners: guidelines for use of the NEMA XR 25 CT dose-check standard’ (AAPM, 2011b) includes a table for suggested notification values. The $CTDI_{vol}$ alert levels for the paediatric head are 50 mGy (age <2 years) and 60 mGy (age 2–5 years); the notification value for the paediatric torso is 10 mGy for age <10 years measured with the 32-cm CT phantom.

5.6. Summary development of optimisation for paediatric imaging

(303) Optimisation of imaging for paediatric patients has additional challenges to those in adult radiology, because of the range in size, tissue composition, and radio-sensitivity with younger age. Digital imaging offers more flexibility in exposures, so that levels can be adapted to the diagnostic requirements for the needs of individual patients. However, in order for this to occur, staff need to be even more aware of dose levels and image quality requirements for diagnosis. The optimisation core team should share bi-directional learning with clinicians, families, and other stakeholders. They should review imaging protocols periodically to implement best practices. Some of the arrangements that might be expected to be in place for x-ray facilities at different levels in the development of optimisation are set out in Box 5.3 to assist in prioritisation of the introduction of arrangements and processes.

Box 5.3. Optimisation arrangements for paediatric radiology that should be in place for facilities at different levels of development and complexity

The arrangements listed below relate specifically to paediatric radiology, and are in addition to those given for the different techniques included in earlier sections. Note that each higher level also includes components from the lower levels.

C: Basic

- Requests for each imaging procedure should include the reason for referral and relevant clinical history of the infant/child.
- Possible alternative non-ionising radiation imaging examinations should be considered.
- Users should optimise equipment features and programmes for patient size and clinical task.
- All personnel involved should understand the importance of preparation and cooperation of the child and family prior to and during imaging examinations.
- Selectable pre-defined study protocols and acquisition programmes for common clinical conditions should be available and optimised for clinical tasks performed with the equipment.

- There should be a standard pregnancy policy with at least verbal and/or written questions for adolescents when pelvic imaging is performed.

B: Intermediate

- Use pre-procedure checklists for paediatric interventional procedures, radiography, and fluoroscopy (e.g. Image Gently, 2022b, c).
- Paediatric diagnostic reference levels (DRLs) should be developed (EU, 2018).
- There is a standard review process to identify patients at higher risk, obtain written consent, and plan all fluoroscopically guided intervention procedures beforehand.
- There are child-friendly facilities and staff have education and training in paediatric care.
- A process for review of near-misses and safety events is enacted for peer learning.

A: Advanced

- Advanced protocols specific to infants and children are available and reviewed regularly by the core team, and there is a process of continuous review of DRLs and use of the median of national dose distributions as an additional tool to improve optimisation.
- There is a support team for imaging that considers childcare, education, safety, quality improvement, anaesthesia for advanced imaging, and child and family preparation.
- A core team is available in paediatric units to provide protocols and techniques to adult/community-based imaging facilities. The core team shares experiences regularly with other clinical teams, health system management, and the public.

(304) Open access internet sources can provide guidance on optimisation and radiological protection relating to children. Many include paediatric imaging protocols, education, and training for the radiology community, referring physicians, staff, and family/carers (WHO, 2016; AAPM, 2022; IAEA, 2022a; WFPI, 2022; Image Gently, 2024).

6. EXAMINATIONS OF PREGNANT PATIENTS

(305) Key points in this section:

- Medical exposure of pregnant patients requires a detailed approach to the process of justification, in which benefits and risks to both mother and the unborn child should be taken into consideration. Imaging methods based on non-ionising radiations (e.g. ultrasound or MRI) that can provide sufficient diagnostic information should always be considered.
- Pregnant patients may be exposed either accidentally early in pregnancy or intentionally when emergency imaging is performed prior to pregnancy status being confirmed. In cases where pregnant patients are exposed, an estimate of conceptus dose may be required. Web-based software packages are available for the calculation of conceptus doses from diagnostic and interventional x-ray procedures.
- Notices should be displayed throughout imaging facilities warning patients who could be pregnant of the risk to the conceptus from an x-ray exposure.
- All patients of childbearing potential should be questioned about pregnancy status before the performance of x-ray examinations in which the conceptus could be exposed directly – the use of a standardised form is recommended.
- The use of patient shielding to reduce conceptus dose is no longer recommended for any type of diagnostic x-ray procedure.
- Low-dose CT protocols should be established for pregnant patients for suitable clinical indications occurring during pregnancy; primary irradiation of the conceptus should be avoided, and emphasis placed on limitation of scan length in the direction of the uterus whenever possible.
- FGI procedures should be optimised, and alternative non-ionising imaging modalities such as sonography or MRI should be considered to accomplish the clinical purpose with reduction in dose to both the conceptus and mother.

6.1. The use of imaging for pregnant patients

(306) Utilisation rates of x-ray imaging in pregnant patients have increased due to the rapid evolution of medical technology, its improved usability, and enhanced accessibility (Lazarus et al., 2009; Goldberg-Stein et al., 2011; Woussen et al., 2016; Kwan et al., 2019). *Publication 103* (ICRP, 2007b) defined the two source-related principles of radiological protection – justification and optimisation – and all medical exposures of pregnant patients must be subject to these in order to minimise exposure of the embryo or fetus. In this section, the term ‘conceptus’ is used to describe all prenatal tissues from the moment of conception until birth, thus including both the embryo and fetus.

(307) Although trauma is the most common condition occurring in pregnant women that leads to imaging procedures, and this often leads to imaging, they also have several medical conditions that occur more frequently than in women of similar age who are not pregnant. Pulmonary embolism is the most common cause of death in pregnant women, accounting for 20% of deaths. Other serious conditions

include cerebrovascular disease, cardiac disease, and bleeding, all of which use complex imaging procedures. Alternative, non-ionising imaging (ultrasound and MRI) are used more frequently in these patients to avoid conceptus exposure to ionising radiation.

6.2. Performance of x-ray procedures on pregnant patients

6.2.1. Justification issues unique to pregnant women

(308) Diagnostic and interventional x-ray examinations require that the radiologist or other radiological medical practitioner, in consultation with the referring physician, justifies that the expected diagnostic benefits of the exposure outweigh the potential risks for the patient; in this case, a balance of effects to the mother and conceptus. *Publication 84* states that ‘After a type of examination or therapy has been justified generally (level 2 justification, further described in *Publication 73*), each specific planned exposure should be justified (level 3 justification)’ (ICRP, 1996, 2000a). Therefore, a detailed approach is required to the process of justification for exposures of pregnant patients, in which benefits and risks to both mother and the unborn child should be taken into consideration. Imaging methods based on non-ionising radiations (e.g. ultrasound or MRI) that can provide sufficient diagnostic information should always be considered. As an example, a standard PA and lateral chest radiograph protocol may be justified in a 25-year-old female, but modification may be needed for a pregnant 25-year-old to a single PA chest radiograph or chest sonography.

(309) In many cases, the mother may benefit from the exposure, but there is no direct benefit for the exposed conceptus. However, a healthy mother is essential for a healthy newborn. If the conceptus does not lie within the primary beam and the dose is low, the risk will be minimal. In that case, the most important thing is to observe good radiological protection practice.

(310) The situation is different if the conceptus is exposed to primary radiation. When a diagnostic or interventional radiologic procedure is medically indicated, the risk to the mother of not doing the procedure will almost always outweigh the risk of harm to the conceptus. Multiple CT examinations (and FGI procedures) may be involved, such as in cases of serious traumatic injuries of pregnant patients, resulting in conceptus doses >50 mGy (Raptis et al., 2014); however, this may be justified to save the mother’s life. Although the imaging management of the pregnant trauma patient should, in most cases, be the same as for any other patient, there is an added need to balance the medical imaging needs of the mother and the conceptus. Therefore, particular attention needs to be paid to radiological protection ethics, as well as justification and optimisation issues in this situation.

(311) The gestational period should also be taken into account during the justification process, as the same type of examination may result in a high or low conceptus dose depending on the size and location of the conceptus in relation to the

primary x-ray beam. For example, an upper abdomen CT examination performed during the first post-conception weeks may result in a conceptus dose <1 mGy, whereas the dose from the same type of examination may be >10 mGy in the third trimester (Damilakis et al., 2010b). Evidence-based guidelines are needed to assist referring physicians in taking the most appropriate decisions regarding x-ray imaging during pregnancy.

6.2.2. Optimisation issues unique to the pregnant patient

(312) Patient positioning should be a special focus for pregnant patients as they cannot lay flat on their back for any length of time in the later stages of pregnancy. Triangular wedge cushioning behind their right side to relieve pressure on the inferior vena cava is important. They may also have gastrointestinal reflux, and require multiple pillows under their upper back and head.

(313) When a pregnant patient undergoes an x-ray examination, the exposure should be optimised. The purpose of optimising diagnostic and interventional x-ray procedures performed on pregnant patients is to minimise the dose of both the expectant mother and conceptus without affecting image quality. Pregnant patients may also be exposed accidentally during the first weeks of gestation. A group of females likely to be exposed accidentally are women with irregular cycles. In fact, approximately 1% of women are exposed to abdominopelvic radiation in the first trimester before they realise they are pregnant. In these cases, pelvic ultrasound for conceptus dating and a realistic estimate of conceptus dose may be needed for patient counselling and reassurance. Fetal doses <100 mGy should never be considered a reason for terminating a pregnancy (ICRP, 2000a), and doses of this magnitude or higher should never occur following any diagnostic exposure.

6.3. Methods for estimating conceptus dose

(314) Pregnant patients may be exposed accidentally early in pregnancy or when emergency imaging is performed prior to pregnancy status being confirmed, or a planned exposure for the mother and conceptus may be justified; in these cases, an estimate of conceptus dose may be required. Web-based software packages are available for the calculation of conceptus doses from diagnostic and interventional x-ray procedures.

(315) Monte Carlo simulations are used to estimate conceptus doses from a variety of diagnostic x-ray examinations performed using a range of exposure factors. A method has been developed to provide normalised dose data to estimate conceptus dose from AP and PA abdominal radiographic and fluoroscopic exposures during all trimesters of gestation (Damilakis et al., 2002a). This method is useful not only in cases of intentional use of radiation during pregnancy but also for accidental exposures. Radiography and fluoroscopy are essential tools for the clinical management of pregnant patients in cases of trauma, but also for the diagnosis

and treatment of other acute conditions such as haemorrhage from splenic aneurysm or intracranial arteriovenous malformation, renal obstruction from stones, cholelithiasis, and placenta accreta. Studies have been published describing methods to estimate dose to a conceptus from cardiac ablation, endoscopic retrograde cholangiopancreatography, and prophylactic hypogastric artery balloon occlusion procedures (Damilakis et al., 2001; Samara et al., 2009; Solomou et al., 2016).

(316) CT is an important imaging method not only for the general population but also for pregnant patients. When MRI is not available immediately, suspected appendicitis after inconclusive ultrasonography, as well as bowel obstruction and trauma, are examples of indications for abdominopelvic CT of the pregnant patient. Other indications include acute mental status changes from cerebral haemorrhage, pulmonary embolism, tumour, and cardiac conditions. Methods have been developed for conceptus dose estimation from standard abdominopelvic CT during the first post-conception weeks (Damilakis et al., 2010a) and during the three trimesters of gestation (Angel et al., 2008). Another study has produced normalised dose data which allow for the estimation of conceptus dose from any CT examination performed on the trunk of the mother (Damilakis et al., 2010b). Conceptus Dose Estimation (CoDE, 2021) is a web-based, freely available software package developed to calculate conceptus doses and radiogenic risks associated with diagnostic and interventional x-ray examinations carried out on pregnant patients. Another software package developed for estimating fetal doses from CT scans (Saltybaeva et al., 2020) is also available through the web (Alkadhi and Saltybaeva, 2022).

(317) Using data provided by these packages, conceptus dose can either be anticipated so that the dose to the unborn child is kept to a minimum, or estimated after the procedure to help the referring physician and the patient make informed decisions regarding the management of pregnancy. Angel et al. (2008) found that the fetal dose from a typical abdominal and pelvic CT ranged from 16 mGy to 31 mGy, with a mean value of 24 mGy. These doses should be lower with modern scanners and optimised protocols.

6.4. Pregnancy assessment before radiologic examinations

(318) When emergency x-ray imaging is needed, the examination should be carried out without delay. Pregnancy status should be obtained as soon as possible after the imaging, and disclosed with the significance of the radiation exposure to the patient and family.

(319) To minimise the frequency of unintended exposures, notices and/or posters should be displayed in the patients' waiting room and other areas of the x-ray department warning patients who could be pregnant of the risk to the conceptus from an x-ray exposure. Example text: 'If you are pregnant or you think you may be pregnant, please inform the doctor or radiographer before the examination'. A picture or illustration of pregnancy will clarify the message and draw more attention to the sign.

(320) All patients of childbearing potential (female, trans, non-binary) should be questioned about pregnancy status before x-ray examinations of the trunk are performed, using a standardised form (SoR, 2023; Badawy et al., 2023). When necessary, thorough investigation of pregnancy status may be needed and should include menstrual history (Damilakis, 2020). If there is uncertainty or when direct exposure of the abdomen/pelvis with CT or an interventional procedure is planned, a urine pregnancy test may be required to determine pregnancy status. In case of a negative result, there should be no hesitation in performing the study.

(321) Adolescent patients (12–18 years old) also need to be asked about their menstrual history and pregnancy status; however, they are particularly vulnerable to social and parental pressures, and there is always a possibility that an adolescent does not provide clear answers. In that case, minors can be asked to undergo a urine pregnancy test prior to CT and FGI procedures involving direct exposure of the abdominopelvic area as well as prior to PET/CT (ACR/SPR, 2018).

(322) The above are general guidelines regarding pregnancy screening before imaging potentially pregnant patients. International and national guidelines are needed to address several issues associated with pregnancy assessment before radiologic examinations (Applegate, 2007). Establishing screening protocols using a multi-disciplinary approach and taking local circumstances into consideration is essential to guide radiologists and other radiological medical practitioners, and avoid accidental exposures.

6.5. Protective shielding of the conceptus

(323) The use of patient shielding has been proposed as a means to reduce conceptus dose from scattered radiation coming from the x-ray tube and examination table, but is no longer generally recommended. In a position statement, AAPM recommended discontinuation of the use of such shielding (AAPM, 2019c), and this issue is considered in Section 2.3.4 and discussed at length in Hiles et al. (2020, 2021). The effectiveness of placing radiological protection garments over part of a patient is limited because most of the conceptus dose from extra-abdominal examinations results from internal scatter within the maternal tissues. However, pregnant patients undergoing diagnostic radiography examinations may sometimes request contact shielding for an examination outside the pelvic region; in such cases, provision of this shielding may offer reassurance and, if in accordance with written procedures, could be at the discretion of the radiographer or imaging facility. Here, accurate collimation is important, and the shielding must not overlay the AEC detectors.

(324) The use of patient shielding to reduce conceptus dose is no longer recommended for fluoroscopic or CT procedures. In some cases, the use of conceptus shielding may have a negative effect on the efficacy of the CT examination. It may elevate the x-ray tube output considerably if part of the shield is inside the exposed volume, increasing the dose to the patient and her fetus, or may produce

artefacts in the CT images if placed within the overscan region of a helical scan, outside the region to be reconstructed (Hiles et al., 2020, 2021). Attention should therefore be paid to minimising scan length rather than the use of shielding.

6.6. Optimisation of x-ray procedures for pregnant patients

6.6.1. Radiography

(325) Radiation risks to a conceptus associated with radiographs performed on the mother are negligible, unless these are performed repeatedly on the abdomen, lumbosacral spine, and pelvis. Nevertheless, the application of dose reduction protocols and techniques during radiography is always ethical practice (ICRP, 2018a). These include adequate x-ray tube filtration, selection of appropriate exposure parameters that result in an acceptable image quality, correct field size, careful collimation of the x-ray beam, proper use or removal of the anti-scatter grid, utilisation of the most dose-efficient x-ray equipment available, and careful selection of the x-ray projection. Protocols that are adjusted to limit the initial number of radiographs for the clinical indication remain common for pregnant patients. A common example is for a single view of the abdomen or chest rather than two views; if the radiologist or other radiological medical practitioner determines that more are justified, they will ask for more. In addition, the PA chest projection is associated with less dose to the conceptus than the AP projection (Damilakis et al., 2002a), as the conceptus is further from the surface on which x rays are incident. A PA projection will also minimise the dose to the breast and oesophagus of the patient. The lateral distance of the unborn child from the primary beam is also of great importance for minimisation of conceptus dose. Conceptus dose can also be reduced by carrying out a chest radiograph with the patient standing because gravity moves the conceptus further from the x-ray field.

(326) It is well known that digital imaging for radiography has the potential for reducing patient radiation doses. The wide dynamic range of FP detectors and post-processing capabilities associated with digital radiography provide several opportunities for dose optimisation and make most image retakes unnecessary. This is especially important for pregnant patients who need radiographic imaging, where care should be taken to select the minimum exposure necessary for the imaging task. Strategies for dose optimisation in digital radiography are discussed in Section 2 of this publication, and other information is available in the literature (IAEA, 2011).

(327) Occasionally, bone mineral density (BMD) assessment is considered beneficial during pregnancy to identify pregnancy-associated osteoporosis and exclude diseases that present similar clinical features. Conceptus dose from a PA spine and femur dual x-ray absorptiometry (DXA) is lower than the average daily natural background in the USA of 8 μ Gy during all trimesters of gestation (Damilakis et al., 2002b). Nevertheless, all measures need to be taken to optimise DXA examinations during pregnancy. Different technologies have been implemented by manufacturers for BMD assessment. The most x-ray-efficient DXA equipment should

always be used. When a DXA scan is needed during the first post-conception weeks, scanning with an empty bladder will expose the conceptus to a lower radiation dose (Damilakis et al., 2002b).

6.6.2. Computed tomography

(328) Pregnant women have unique physiology that leads to increased risk of conditions requiring cross-sectional imaging. One example is the effect of the doubling of blood volume that impacts the heart; also, when considering intravenous contrast and evaluation of CT pulmonary angiography, the dilution effect can result in suboptimal examinations. Therefore, optimisation in pregnant patients is a challenging task that requires deep knowledge of both the clinical status/indication and the specific parameters and dose reduction tools available during data acquisition and post-processing. The establishment of specific low-dose acquisition protocols based on clinical indications needed for pregnant patients, such as urinary tract stone disease, appendicitis, and pulmonary embolism, is of paramount importance. Whenever possible, primary irradiation of the conceptus should be avoided. A simple and very effective way of minimising the dose to both the patient and her growing child without affecting image quality is scan range reduction. Examples of CT-guided procedures in pregnant patients can be found at Image Wisely (2022b).

(329) Helical acquisition mode is superior to sequential mode, mainly because of its speed. However, helical mode is associated with extra exposure due to additional rotations needed for image reconstruction of the first and last slice of the imaged volume (z-overscanning), which may increase dose to peripheral regions of the scan with larger pitches (see Section 4.2.4). Modern CT scanners use dynamic adaptive section collimation to block the dose from z-overscanning. For scanners without dynamic collimators, proper selection of beam collimation, pitch, and reconstruction slice thickness is needed to restrict the extent of z-overscanning (Tzedakis et al., 2005). This is particularly important when the conceptus lies near the margin of the planned image volume. The relative contribution of the extra exposure due to z-overscanning may be considerable, especially when the planned image volume is limited.

(330) IR and DLIR have been introduced for CT with the aim of reducing image noise. Advantage can be taken of IR/DLIR to adjust exposure factors to lower the dose to the patient and conceptus while achieving a similar level of image quality to FBP reconstruction (Section 4.3). The use of IR/DLIR is recommended for CT examinations of pregnant patients.

(331) Patient centring affects both patient dose and image quality. Although pregnant patient centring errors do not affect conceptus dose significantly, improper alignment may affect image quality adversely (Solomou et al., 2015). It is, therefore, recommended that pregnant patients are always accurately aligned at the gantry isocentre.

(332) Several CT dose reduction tools have been developed over recent years for the modulation of tube current and x-ray tube potential. ATCM tools tailor the tube current on the basis of each patient's body habitus to produce images of diagnostic quality at the minimum possible radiation dose (see Section 4.4). Conceptus dose may be reduced considerably when the ATCM tool is activated (Solomou et al., 2015). CT manufacturers have recently combined ATCM tools with ATVS algorithms that allow for automatic selection of x-ray tube potential and tube current settings. To minimise radiation dose to superficial dose-sensitive organs, such as the eye, thyroid, and breast, organ-based tube current modulation systems reduce the x-ray tube output over the anterior part of the patient's body circumference. The effect of these systems on radiation dose to tissues and organs located in the central area of a patient's body, such as the conceptus, is not known. Activation of organ-based tube current modulation systems during abdominal CT examinations is not recommended.

(333) It should always be borne in mind that CT scanning in the pregnant patient, especially when outside of the abdomen and pelvis, provides low amounts of internal scatter to the fetus and can be lifesaving to both mother and fetus. An example case illustrating some of the issues and decisions regarding the choice of imaging technique for pregnant patients is given for CT pulmonary angiography.

(334) A pregnant patient presents with suspected pulmonary embolism. Multi-specialty guidelines suggest the avoidance of ionising radiation by using ultrasound of the lower extremity veins for evaluation of deep venous thrombosis. Multi-specialty guidelines suggest the avoidance of ionising radiation by using ultrasound of the lower extremity veins for evaluation of deep venous thrombosis. If positive, treat accordingly. If uncertainty remains, either lung scintigraphy or CT angiography are used. While lung perfusion scintigraphy to diagnose pulmonary embolism provides the lowest dose to the mother, it does not always provide as much clinical information. CT pulmonary angiography delivers a higher dose to the breast and lung of the pregnant patient than lung perfusion scintigraphy, but provides more clinical information including alternative diagnoses that are critically important (lung, cardiac) and, often more importantly, the procedure is readily available at any time of day. For these reasons and the continued dose lowering CT technology, CT pulmonary angiography is considered by many to be the test of choice for the diagnosis of pulmonary embolism (Leung et al., 2012; Colak et al., 2021). Of note, however, is that maternal radiogenic cancer risks from both CT pulmonary angiography and lung perfusion scintigraphy are very low. The decision as to whether to proceed with CT pulmonary angiography or scintigraphy to rule out suspected pulmonary embolism in pregnant patients often depends on equipment availability and referring physician preferences. A study showed that a reduced z-axis protocol for CT pulmonary angiography in pregnancy extending from the aortic arch to the base of the heart can reduce radiation dose by 71% without affecting the diagnosis (Shahir et al., 2015). More details and an example of a protocol can be found at Image Wisely (2022b).

(335) CT coronary angiography should be considered for pregnant patients with suspected cardiovascular disease. All modern CT scanners are capable of varying tube current output in synchrony with the patient's ECG. An effective radiation dose-saving technique in CT coronary angiography is prospective ECG-triggered scanning (see Section 4.5.2). When performing CT coronary angiography examinations on pregnant patients, this technique should be preferred over retrospective acquisition. If retrospective acquisition mode is needed, ECG-based mA modulation should be employed.

(336) On scanners that adjust mAs and pitch independently, pitch values <1.0 should be used with caution as they may increase conceptus dose for abdominal and pelvic CT examinations, but adjustments in mAs may be made to compensate if required. Limiting the number of CT phases through the abdomen and pelvis will reduce conceptus dose considerably, provided that the expected diagnostic information can still be obtained with confidence. In general, repeat scanning through the conceptus should be avoided. Box 6.1 summarises the most important ways to constrain the dose to the conceptus when performing CT examinations.

Box 6.1. Practical ways to control conceptus dose from computed tomography examinations

- Avoid primary irradiation of the conceptus if at all possible.
- Computed tomography (CT) scanning in the pregnant patient, especially when outside of the abdomen and pelvis, provides low amounts of internal scatter to the fetus and can be lifesaving to both mother and fetus.
- Establish low-dose acquisition protocols based on clinical indications for pregnant patients.
- Pay careful attention to minimising scan length, as reductions of 1–3 cm can reduce fetal doses by approximately one-quarter for chest scans and one-half for scans of the upper abdomen (Hiles et al., 2020).
- Avoid the use of pitch values <1.0 for scanners that adjust mAs and pitch independently, especially for abdominal and pelvic examinations, if appropriate (see Section 4.2.4).
- Limit the number of CT phases through the abdomen and pelvis as much as possible (e.g. virtual non-contrast technique using dual-energy equipment).
- Use dose reduction tools such as automatic tube current modulation with caution (see Section 4.4).
- Use iterative or deep-learning-based image reconstruction, and reduce exposure factors to take account of the resulting improvement in image quality.
- Align pregnant patients accurately at the gantry isocentre.

6.6.3. Optimisation in fluoroscopically guided interventional procedures

(337) Occasionally, pregnant patients are exposed to ionising radiation from FGI procedures, such as endovascular coiling in trauma, vascular dissection or malformation bleeding, percutaneous aspiration or removal of symptomatic ovarian cysts/tumours, stent or nephrostomy placements for renal obstruction from stones, radio-frequency cardiac catheter ablation, and endoscopic retrograde cholangiopancreatography. Alternative non-ionising imaging modalities, such as ultrasound or MRI, should be considered to accomplish the clinical purpose, where possible.

(338) Optimisation of all FGI procedures is needed to accomplish the clinical purpose with the maximum possible dose reduction for the conceptus and the mother. The same applies to CT-guided interventions. FGI procedures in the anatomic regions of the thorax, head/neck, and extremities are associated with low conceptus dose (McCollough et al., 2007). For example, a typical catheter ablation procedure performed on young female patients requiring 0.58-, 23-, 5.3-, and 10.2-min exposures for groin-to-heart PA, PA, right anterior oblique, and left anterior oblique projections, respectively, is associated with a conceptus dose <1 mGy during all trimesters of gestation (Damilakis et al., 2001). If the conceptus is likely to be in, or proximal to, the primary beam, conceptus doses can be much higher. Ways in which the operator can reduce the dose to the conceptus when performing FGI procedures are listed in Box 6.2.

Box 6.2. Practical ways to control conceptus dose during fluoroscopically guided interventional procedures

- Collimate the beam carefully.
- Keep the exposure time as short as possible.
- Use as high a tube potential as possible.
- Avoid overuse of the magnification mode.
- Keep the x-ray tube as far away from the patient as possible and the detector close to the patient.
- Use low-dose-rate pulsed fluoroscopy.
- Use last series hold (also referred to as ‘video loop’) when available.
- Keep the dose from digital subtraction angiography to a minimum.
- Consider using ultrasound guidance for catheter insertion, and choose a route that reduces conceptus dose.
- Determine the optimal status of the maternal bladder in relation to the type of projections needed for the procedure.

(339) Dose management systems are considered important tools for ensuring patient safety and image quality (ICRP, 2023). Information provided can be used for the selection of the most dose-efficient equipment for the pregnant patient, and the development of acquisition protocols that deliver the lowest radiation dose to the

unborn child without sacrificing diagnostic image quality. While patient exposure tracking may have several advantages, care must be taken to make sure that conceptus dose estimation methods used by dose management systems are appropriate and dose data analysis is performed by an experienced medical physicist.

7. CONCLUSIONS

(340) Optimisation in digital radiology requires provision of clinical images for individual patients that are of sufficient quality to ensure accurate and reliable diagnosis to enable correct care decisions to be made. The radiation doses used to acquire the clinical images should be adjusted to the minimum level appropriate – and locally available – for the imaging technology, clinical indication, and individual patient’s needs. This publication brings together practical aspects of optimisation of radiological protection for the various digital radiology modalities (radiography, fluoroscopy, and CT), all of which require similar approaches, but with slightly different methods in their application.

(341) *Publication 154* set out three building blocks on which strategies for achieving optimisation should be built (ICRP, 2023). The cornerstone is collaboration between radiological professionals, with radiologists, other radiological medical practitioners, radiographers, and medical physicists working together as a team within an organisation that provides a structure for these processes. The radiologist and other radiological medical practitioner (or radiographer) can judge whether the image quality is sufficient for the diagnostic purpose, the radiographer knows the practical operation and limitations of the equipment, and the medical physicist understands the physical principles behind image formation, and can perform and interpret measurements of dose and image quality. Success of this collaboration depends on members of the optimisation team recognising the skills of the other members, and working together with mutual respect in their different roles. On a broader scale, department managers, clinical directors, and vendor representatives have a role in the collaboration. Increasing technical and computational complexity in radiology equipment and applications increases the importance of this multi-professional approach and the dependency on the combined knowledge of different professionals.

(342) This publication is aimed primarily at radiologists and other radiological medical practitioners, radiographers, and medical physicists, but should also be understood by managers, all fluoroscopy operators, regulators, equipment manufacturers, and expert societies/organisations. There will be parts that are more suitable for one or other group. For example, in Section 2 on radiography, some parts deal with optimisation as part of the day-to-day work of the radiographer. On the other hand, there are parts of Sections 2, 3, and 4 that deal with aspects of equipment performance set up during commissioning which are of more relevance to medical physicists, but that need to be taken forward in discussion with radiologists, other radiological medical practitioners, and radiographers. There are also approaches for interventional procedures in Section 3 which will be of prime interest to the radiological medical practitioners who perform them, but of relevance to other groups.

(343) Technological innovations are being implemented continually that have the potential to provide a higher degree of optimisation. Assessments of aspects of image quality as well as radiation dose are now used in controlling exposure

levels. As the level of sophistication develops, the variety and complexity of procedures that are possible increases. In order to make full use of new features, the performance of equipment needs to be monitored and analysed, and examination protocols need to be refined as more experience is gained.

(344) This publication provides a message for management in emphasising the need for staff to receive comprehensive initial training in the use of imaging equipment and software. It also reinforces the requirement for the continuation of career-long training to ensure that the full potential of new techniques, as they become available, can be realised. Management must commit to provide both resources and organisational processes that ensure a culture of radiation safety and of continual improvement in optimisation.

(345) Vendors need to provide sufficient information and training about the operation and proper use of features that allow dose levels on new equipment to be set at optimum levels for all local patient populations. This becomes ever more important as equipment with new features is purchased by a wider variety of facilities. Vendors should provide an additional level of assistance where equipment features are introduced for the first time into countries that may not have the level of medical physics support and experience to ensure that the features are set up properly at the start and used effectively thereafter.

(346) Operation of all digital radiology imaging involves the need for understanding the interdependence of patient dose and image quality. This publication discusses these aspects where they relate to performance of a particular type of equipment. Readers are directed to *Publication 154* for more detailed consideration of dose audit and image quality analysis (ICRP, 2023), and to *Publication 135* in relation to the use of DRLs (ICRP, 2017).

(347) The key message is that continual striving for optimisation is an essential requirement for an efficient digital radiology service. This publication provides information that should be of value to radiology staff and facilities in achieving this.

REFERENCES

- AAPM, 2001. Cardiac Catheterisation Equipment Performance. AAPM Report Number 70. American Association of Physicists in Medicine, New York.
- AAPM, 2006. Quality Assurance of Computed and Digital Radiography Systems. Acceptance Testing and Quality Control of Photostimulable Storage Phosphor Imaging Systems. Report No. 93. AAPM Task Group 10. American Association of Physicists in Medicine, New York.
- AAPM, 2009. An Exposure Indicator for Digital Radiography. Report of AAPM Radiography and Fluoroscopy Subcommittee Task Group 116. American Association of Physicists in Medicine, New York.
- AAPM, 2011a. Size-specific Dose Estimates (SSDE) in Pediatric and Adult Body CT Examinations. Report of AAPM Task Group 204. American Association of Physicists in Medicine, New York.
- AAPM, 2011b. Recommendations Regarding Notification and Alert Values for CT Scanners: Guidelines for Use of the NEMA XR 25 CT Dose-Check Standard. American Association of Physicists in Medicine, New York. Available at: <https://www.aapm.org/pubs/CTProtocols/documents/NotificationLevelsStatement.pdf> (last accessed August 2022).
- AAPM, 2012. Functionality and Operation of Fluoroscopic Automatic Brightness Control/ Automatic Dose Rate Control Logic in Modern Cardiovascular and Interventional Angiography Systems. AAPM Report No. 125. American Association of Physicists in Medicine, New York.
- AAPM, 2014. Use of Water Equivalent Diameter for Calculating Patient Size and Size-specific Dose Estimates (SSDE) in CT. Report of AAPM Task Group 220. American Association of Physicists in Medicine, New York.
- AAPM, 2015. Ongoing quality control in digital radiography: Report of AAPM Imaging Physics Committee Task Group 151. Med. Phys. 42, 6658–6670.
- AAPM, 2018. Current state of practice regarding digital radiography exposure indicators and deviation indices: Report of AAPM Imaging Physics Committee Task Group 232. Med. Phys. 45, e1146–e1160.
- AAPM, 2019a. Estimating Patient Organ Dose with Computed Tomography: a Review of Present Methodology and Required DICOM Information. A Joint Report of AAPM Task Group 246 and the European Federation of Organizations for Medical Physics (EFOMP). American Association of Physicists in Medicine, New York. Available at: https://www.aapm.org/pubs/reports/RPT_246.pdf (last accessed October 2020).
- AAPM, 2019b. Performance Evaluation of Computed Tomography Systems. Report of AAPM Task Group 233. American Association of Physicists in Medicine, New York. Available at: <https://aapm.org/pubs/reports/detail.asp?docid=186> (last accessed August 2022).
- AAPM, 2019c. Position Statement on the Use of Patient Gonadal and Fetal Shielding. American Association of Physicists in Medicine, New York. Available at: <https://www.aapm.org/org/policies/details.asp?id=468&type=PP> (last accessed October 2020).
- AAPM, 2020. Principles and Applications of Multi-energy CT: Report of AAPM Task Group 291. American Association of Physicists in Medicine, New York. Available at: <https://www.aapm.org/pubs/reports/detail.asp?docid=201> (last accessed December 2024).
- AAPM, 2022. The Alliance for Quality Computed Tomography. Reference CT Protocols. American Association of Physicists in Medicine, New York. Available at: <https://www.aapm.org/pubs/CTProtocols/default.asp> (last accessed January 2022).

- AAPM, 2023. AAPM Task Group Report 305: Guidance for standardization of vendor-neutral reject analysis in radiography. *J. Appl. Clin. Med. Phys.* 24, e13938.
- AAPM/EFOMP, 2023. Breast Dosimetry for Standard and Contrast-enhanced Mammography and Breast Tomosynthesis. Joint AAPM Task Group 282/EFOMP Working Group Report. American Association of Physicists in Medicine, New York. Available at: <https://www.aapm.org/pubs/reports/detail.asp?docid=276>.
- Achenbach, S., Marwan, M., Ropers, D., et al., 2010. Coronary computed tomography angiography with a consistent dose below 1 mSv using prospectively electrocardiogram-triggered high-pitch spiral acquisition. *Eur. Heart J.* 31, 340–346.
- ACR, 2021. Manual on Contrast Media. American College of Radiology, Reston, VA. Available at: <https://www.acr.org/Clinical-Resources/Contrast-Manual> (last accessed January 2022).
- ACR, 2022. ACR CT Accreditation Program. American College of Radiology, Reston, VA. Available at: <https://www.acraccreditation.org/modalities/ct> (last accessed August 2022).
- ACR/AAPM/SIIM/SPR, 2022. Practice parameter for digital radiography. Revised 2022. American College of Radiology, Reston, VA. Available at: <https://www.acr.org/-/media/ACR/Files/Practice-Parameters/Rad-Digital.pdf> (last accessed 15 January 2025).
- ACR/SPR, 2018. Practice Parameter for Imaging Pregnant or Potentially Pregnant Adolescents and Women with Ionizing Radiation. Resolution 39. American College of Radiology, Reston, VA. Available at: <https://www.acr.org/-/media/acr/files/practice-parameters/pregnant-pts.pdf> (last accessed December 2021).
- ACR/RSNA, 2020. The Radiology Information Resource for Patients. American College of Radiology, Reston, VA. Available at: <https://www.radiologyinfo.org/> (last accessed October 2020).
- ACR/DIR, 2022. Dose Index Registry for CT Scan Doses. American College of Radiology, Reston, VA. Available at: <https://www.acr.org/Practice-Management-Quality-Informatics/Registries/Dose-Index-Registry> (last accessed August 2022).
- Akai, H., Kiryu, S., Shibata, E., et al., 2016. Reducing CT radiation exposure with organ effective modulation: a retrospective clinical study. *Eur. J. Radiol.* 85, 1569–1573.
- Alhailiy, A.B., Ekpo, E.U., Kench, P.L., Ryan, E.A., Brennan, P.C., McEntee, M., 2019. The associated factors for radiation dose variation in cardiac CT angiography. *Br. J. Radiol.* 92, 20180793.
- Alkadhi, H., Saltybaeva, N., 2022. Fetal Radiation Dose Assessment. Institute of Diagnostic and Interventional Radiology, University Hospital Zurich, Zurich. Available at <https://www.fetaldose.org/> (last accessed October 2022).
- Almén, A., Gujónsdóttir, J., Heimland, N., et al., 2022. Paediatric diagnostic reference levels for common radiological examinations using the European guidelines. *Br. J. Radiol.* 95, 20210700.
- Alsleem, H., Davidson, R., Al-Dhafiri, B., Alsleem, R., Ameer, H., 2019. Evaluation of radiographers' knowledge and attitudes of image quality optimisation in paediatric digital radiography in Saudi Arabia and Australia: a survey-based study. *J. Med. Radiat. Sci.* 66, 229–237.
- Angel, E., Wellnitz, C.V., Goodsitt, M.M., et al., 2008. Radiation dose to the fetus for pregnant patients undergoing multidetector CT imaging: Monte Carlo simulations estimating fetal dose for a range of gestational age and patient size. *Radiology* 249, 220–227.
- Applegate, K., 2007. Pregnancy screening of adolescents and women before radiologic testing: does radiology need a national guideline? *J. Am. Coll. Radiol.* 4, 533–536.

- Arellano, R.S., Yang, K., Rehani, M.M., 2021. Analysis of patients receiving ≥ 100 mSv during a computed tomography intervention. *Eur. Radiol.* 31, 3065–3070.
- Arndt, C., Güttler, F., Heinrich, A., et al., 2021. Deep learning CT image reconstruction in clinical practice. *Rofo.* 193, 252–261.
- Aschoff, A.J., Catalano, C., Kirchin, M.A., Krix, M., Albrecht, T., 2017. Low radiation dose in computed tomography: the role of iodine. *Br. J. Radiol.* 90, 20170079.
- Aufrichtig, R., Xue, P., Thomas, C.W., Gilmore, G.C., Wilson, D.L., 1994. Perceptual comparison of pulsed and continuous fluoroscopy. *Med. Phys.* 21, 245–256.
- Badawy, M.K., Dadoo, P., Grossmann, K., Lane, R., Colon-Cabrera, D., 2023. Gender-inclusive practice in pregnancy determination for transgender, gender diverse and non-binary patients in medical imaging. *J. Med. Imaging Radiat. Oncol.* 67, 625–633.
- Balter, S., Fletcher, D., Kuan, H., et al., 2002. Techniques to Estimate Radiation Dose to Skin During Fluoroscopically Guided Procedures. *Skin Dose Measurements AAPM*. Available at: <https://www.aapm.org/meetings/02am/pdf/8368-40188.pdf> (last accessed August 2022).
- Balter, S., Hopewell, J.W., Miller, D.L., Wagner, L.K., Zelefsky, M.J., 2010. Fluoroscopically guided interventional procedures: a review of radiation effects on patients' skin and hair. *Radiology* 254, 326–341.
- Balter, S., 2019. Fluoroscopic technology from 1895 to 2019. Drivers: physics and physiology. *Med. Phys. Int. J.* 2, 111–140.
- Barrett, T., Bowden, D.J., Shaida, N., et al., 2012. Virtual unenhanced second generation dual-source CT of the liver: is it time to discard the conventional unenhanced phase? *Eur. J. Radiol.* 81, 1438–1445.
- Bednarek, D., Barbarits, J., Rana, V.K., Nagaraja, S.P., Josan, M.S., Rudin, S., 2011. Verification of the performance accuracy of a real-time skin-dose tracking system for interventional fluoroscopic procedures. *Proc. SPIE Int. Soc. Opt. Eng.* 7961, 638–645.
- Bly, R., Järvinen, H., Kaijaluoto, S., Ruonala, V., 2020. Contemporary collective effective dose to the population from x-ray and nuclear medicine examinations – changes over last 10 years in Finland. *Radiat. Prot. Dosimetry* 189, 318–322.
- Boone, J.M., Geraghty, E.M., Seibert, J.A., Wootton-Gorges, S.L., 2003. Dose reduction in paediatric CT: a rational approach. *Radiology* 228, 352–360.
- Boone, J.M., 2009. Method for evaluating bow tie filter angle-dependent attenuation in CT: theory and simulation results. *Med. Phys.* 37, 40–48.
- Boos, J., Thomas, C., Appel, E., et al., 2018. Institutional computed tomography diagnostic reference levels based on water-equivalent diameter and size-specific dose estimates. *J. Radiol. Prot.* 38, 536–548.
- Bordier, C., Klausz, R., Desponds, L., 2015. Patient dose map indications on interventional x-ray systems and validation with Gafchromic XR-RV3 film. *Radiat. Prot. Dosimetry* 163, 306–318.
- Borges, A.P., Antunes, C., Curvo-Semedo, L., 2023. Pros and cons of dual-energy CT systems: 'one does not fit all'. *Tomography* 9, 195–216.
- Bui, A.L., Dieleman, J.L., Hamavid, H., et al., 2017. Spending on children's personal health care in the United States, 1996–2013. *JAMA Pediatr.* 171, 181–189.
- Buls, N., Pages, J., Mana, F., Osteaux, M., 2002. Patient and staff exposure during endoscopic retrograde cholangiopancreatography. *Br. J. Radiol.* 75, 435–443.
- Busch, H.P., Faulkner, K., 2005. Image quality and dose management for digital radiography. *Radiat. Prot. Dosimetry* 117, 143–147.
- Carroll, Q.B., 2018. *Radiography in the Digital Age*, third ed. C.C. Thomas, Springfield, IL.

- Carlton, R.R., Adler, A.M., Balac, V., 2019. *Principles of Radiographic Imaging: an Art and a Science*, sixth ed. Cengage Learning, Boston, MA.
- Chung, R., Dane, B., Yeh, B.M., Morgan, D.E., Sahani, D.V., Kambadakone, A., 2023. Dual-energy computed tomography: technological considerations. *Radiol. Clin. North Am.* 61, 945–961.
- CoDE, 2021. Concert: Conceptus Radiation Doses and Risks from Imaging with Ionizing Radiation. University of Crete, Heraklion. Available at: <http://embryodose.med.uoc.gr/> (last accessed December 2021).
- Cohen, M.D., Cooper, M.L., Piersall, K., Apgar, B.K., 2011. Quality assurance: using the exposure index and the deviation index to monitor radiation exposure for portable chest radiographs in neonates. *Pediatr. Radiol.* 41, 592–601.
- Colak, E., Kitamura, F.C., Hobbs, S.B., et al., 2021. The RSNA pulmonary embolism CT dataset. *Radiol. Artif Intell.* 3, e200254.
- COMARE, 2021. Radiological Dose Issues with Interventional Radiology Within the UK. Committee on Medical Aspects of Radiation in the Environment, 19th Report. Public Health England, Chilton. Available at: <https://www.gov.uk/government/publications/radiological-dose-issues-with-interventional-radiology-in-he-uk> (last accessed December 2021).
- CTisus, 2022. Everything you Need to Know About Computed Tomography (CT) & CT Scanning. CT Scan Protocols. Johns Hopkins University, Baltimore, MD. Available at: <https://www.ctisus.com/responsive/protocols> (last accessed January 2022).
- Curry, T.S., Dowdey, J.E., Murry, R.C., 1990. *Christensen's Physics of Diagnostic Radiology*. Lippincott Williams & Wilkins, Philadelphia, PA, pp. 93–98.
- Damilakis, J., Theocharopoulos, N., Perisinakis, K., et al., 2001. Conceptus radiation dose and risk from cardiac catheter ablation procedures. *Circulation* 104, 893–897.
- Damilakis, J., Tzedakis, A., Sideri, L., Perisinakis, K., Stamatelatos, I.E., Gourtsoyiannis, N., 2002a. Normalized conceptus doses for abdominal radiographic examinations calculated using a Monte Carlo technique. *Med. Phys.* 29, 2641–2648.
- Damilakis, J., Perisinakis, K., Vrahoriti, H., Kontakis, G., Varveris, H., Gourtsoyiannis, N., 2002b. Embryo/fetus radiation dose and risk from dual x-ray absorptiometry examinations. *Osteoporos. Int.* 13, 716–722.
- Damilakis, J., Perisinakis, K., Tzedakis, A., Papadakis, A., Karantanis, A., 2010a. Radiation dose to the embryo from NDCT during early gestation: a method that allows for variations in maternal body size and embryo position. *Radiology* 257, 483–489.
- Damilakis, J., Tzedakis, A., Perisinakis, K., Papadakis, A.E., 2010b. A method of estimating embryo doses resulting from multidetector CT examinations during all stages of gestation. *Med. Phys.* 37, 6411–6420.
- Damilakis, J., 2020. The management of (a) pregnant patients and (b) pregnant employees. In: Damilakis, J. (Ed.), *Radiation Dose Management of Pregnant Patients, Pregnant Staff and Paediatric Patients*. Diagnostic and Interventional Radiology. IOP Publishing, Bristol, pp. 8.1–8.10.
- Dane, B., O'Donnell, T., Liu, S., et al., 2021. Radiation dose reduction, improved isocenter accuracy and CT scan time savings with automatic patient positioning by a 3D camera. *Eur. J. Radiol.* 136, 109537.
- D'Angelo, T., Cicero, G., Mazziotti, S., et al., 2019. Dual energy computed tomography virtual monoenergetic imaging: technique and clinical applications. *Br. J. Radiol.* 92, 20180546.

- Dauer, L.T., Thornton, R.H., Miller, D.L., et al., 2012. Radiation management for interventions using fluoroscopic or computed tomographic guidance during pregnancy: a joint guideline of the Society of Interventional Radiology and the Cardiovascular and Interventional Radiological Society of Europe with Endorsement by the Canadian Interventional Radiology Association. *J. Vasc. Interv. Radiol.* 23, 19–32.
- Dave, J.K., Jones, A.K., Fisher, R., et al., 2018. Current state of practice regarding digital radiography exposure indicators and deviation indices: Report of AAPM Imaging Physics Committee Task Group 232. *Med. Phys.* 45, e1146–e1160.
- de Basea Gomez, M.B., Thierry-Chef, I., Harbron, R., et al., 2023. Risk of hematological malignancies from CT radiation exposure in children, adolescents and young adults. *Nat. Med.* 29, 3111–3119.
- Dixon, M.T., Loader, R.J., Stevens, G.C., Rowles, N.P., 2016. An evaluation of organ dose modulation on a GE optima CT660-computed tomography scanner. *J. Appl. Clin. Med. Phys.* 17, 380–391.
- Don, S., 2004. Radiosensitivity of children: potential for overexposure in CR and DR and magnitude of doses in ordinary radiographic examinations. *Pediatr. Radiol.* 34, S167–S172.
- Don, S., Sensakovic, W.F., Gress, D., Zacharias-Andrews, K., 2021. ACR Dose Index Registry – digital radiography pilot. *J. Am. Coll. Radiol.* 18, 1213–1215.
- Donnelly, L.F., Emery K.H., Brody, A.S., et al., 2001. Minimizing radiation dose for pediatric body applications of single-detector helical CT. *AJR Am. J. Roentgenol.* 176, 303–306.
- Dorfman, A.L., Fazel, R., Einstein, A.J., et al., 2011. Use of medical imaging procedures with ionizing radiation in children: a population-based study. *Arch. Pediatr. Adolesc. Med.* 165, 458–464.
- Dovales, A.C.M., da Rosa, L.A.R., Kesminiene, A., et al., 2016. Patterns and trends of computed tomography usage in outpatients of the Brazilian public healthcare system, 2001–2011. *J. Radiol. Prot.* 36, 547–560.
- Doyle, P., Martin, C.J., 2006. Calibrating automatic exposure control devices for digital radiography. *Phys. Med. Biol.* 51, 5475–5485.
- Eberhard, M., Mergen, V., Higashigaito, K., et al., 2021. Coronary calcium scoring with first generation dual-source photon-counting CT – first evidence from phantom and in-vivo scans. *Diagnostics (Basel)* 11, 1708.
- EC, 1995. European Guidelines on Quality Criteria for Diagnostic Radiographic Images. EUR 16260 EN. European Commission, Brussels.
- EC, 2004. Image Quality and Dose Management for Digital Radiography. DIMOND III Report. European Commission, Brussels. Available at: https://www.sorfi.fi/doc/diamond_III.pdf (last accessed October 2019).
- EC, 2012. Criteria for Acceptability of Medical Radiological Equipment used in Diagnostic Radiology, Nuclear Medicine and Radiotherapy. Radiation Protection Report No. 162. European Commission, Luxembourg.
- EFOMP/ESTRO/IAEA, 2019. Quality Control in Cone-beam Computed Tomography (CBCT). EFOMP/ESTRO/IAEA Protocol. European Federation of Organisations for Medical Physics, Utrecht. Available at: https://www.efomp.org/uploads/2d23d153-b77c-4161-802c-5b8422d15e29/EFOMP_IAEA_ESTRO_%20CBCT_2019_05_27.pdf (last accessed July 2020).
- Ekpo, E.U., Adejoh, T., Akwo, J.D., et al., 2018. Diagnostic reference levels for common computed tomography (CT) examinations: results from the first Nigerian nationwide dose survey. *J. Radiol. Prot.* 38, 525–535.

- Esteva, A., Robicquet, A., Ramsundar, B., et al., 2019. A guide to deep learning in healthcare. *Nat. Med.* 25, 24–29.
- ESR, 2020. Eurosafe Imaging Website. European Society of Radiology, Vienna. Available at: <http://www.eurosafeimaging.org/> (last accessed October 2020).
- EU, 2018. European Guidelines on Diagnostic Reference Levels for Paediatric Imaging (PiDRLs). Radiation Protection No. 185. European Union, Luxembourg. Available at: <http://www.eurosafeimaging.org/pidrl> (last accessed August 2022).
- Fang, T., Deng, W., Law, M.W.-M., et al., 2018. Comparison of image quality and radiation exposure between conventional imaging and gemstone spectral imaging in abdominal CT examination. *Br. J. Radiol.* 91, 20170448.
- Farah, J., Trianni, A., Ciraj-Bjelac, O., et al., 2015. Characterization of XR-RV3 GafChromic films in standard laboratory and in clinical conditions and means to evaluate uncertainties and reduce errors. *Med. Phys.* 42, 4211–4226.
- Fernandez-Soto, J.M., Ten, J.I., Sanchez, R.M., España, M., Pifarre, X., Vañó, E., 2015. Benefits of an automatic patient dose registry system for interventional radiology and cardiology at five hospitals of the Madrid area. *Radiat. Prot. Dosimetry* 165, 53–56.
- Filev, P.D., Mittal, P.K., Tang, X., et al., 2016. Increased computed tomography dose due to miscentering with use of automated tube voltage selection: phantom and patient study. *Curr. Probl. Diagn. Radiol.* 45, 265–270.
- Fisher, R.F., Applegate, K.E., Berkowitz, L.K., et al., 2021. AAPM Medical Physics Practice Guideline 12.a: Fluoroscopy dose management. *J. Appl. Clin. Med. Phys.* 23, e13526.
- Fletcher, D.W., Miller, D.L., Balter, S., Taylor, M.A., 2002. Comparison of four techniques to estimate radiation dose to skin during angiographic and interventional radiology procedures. *J. Vasc. Interv. Radiol.* 13, 391–397.
- Flohr, T., Petersilka, M., Henning, A., Ulzheimer, S., Ferda, J., Schmidt, B., 2020. Photon-counting CT review. *Phys. Med.* 79, 126–136.
- Foster, L.P., Clark, K.R., 2019. Pediatric radiography education: a survey of recent graduates' experiences. *Radiol. Technol.* 91, 18–26.
- George, E., Wortman, J.R., Fulwadhva, U.P., Uyeda, J.W., Sodickson, A.D., 2017. Dual energy CT applications in pancreatic pathologies. *Br. J. Radiol.* 90, 20170411.
- Gibson, D.J., Davidson, R.A., 2012. Exposure creep in computed radiography: a longitudinal study. *Acad. Radiol.* 19, 458–462.
- Goldberg-Stein, S., Liu, B., Hahn, P.F., et al., 2011. Body CT during pregnancy: utilization trends, examination indications, and fetal radiation doses. *AJR Am. J. Roentgenol.* 196, 146–151.
- Goske, M.J., Charkot, E., Herrmann, T., et al., 2011. Image Gently: challenges for radiologic technologists when performing digital radiography in children. *Pediatr. Radiol.* 41, 611–619.
- Gottumukkala, R.V., Kalra, M.K., Tabari, A., Otrakji, A., Gee, M.S., 2019. Advanced CT techniques for decreasing radiation dose, reducing sedation requirements, and optimizing image quality in children. *Radiographics* 39, 709–726.
- Graser, A., Johnson, T.R.C., Hecht, E.M., et al., 2009. Dual-energy CT in patients suspected of having renal masses: can virtual non-enhanced images replace true non-enhanced images? *Radiology* 252, 433–440.
- Greffier, J., Van Ngoc Ty, C., Agelou, M., et al., 2017. Impact of the calibration conditions of XR-RV3 films on peak skin dose measurements in interventional radiology. *Radiat. Prot. Dosimetry* 174, 207–215.

- Hara, A.K., Paden, R.G., Silva, A.C., Kujak, J.L., Lawder, H.J., Pavlicek, W., 2009. Iterative reconstruction technique for reducing body radiation dose at CT: feasibility study. *AJR Am. J. Roentgenol.* 193, 764–771.
- Hart, D., Wall, B.F., Hillier, M.C., Shrimpton, P.C., 2010. Frequency and Collective Dose for Medical and Dental X-ray Examinations in the UK. 2008 Report HPA-CRCE-012. Health Protection Agency, Chilton.
- Hassan, A., Nazir, S.A., Alkadhi, H., 2011. Technical challenges of coronary CT angiography: today and tomorrow. *Eur. J. Radiol.* 79, 161–171.
- HealthIT, 2013. Shared Decision Making. The Office of the National Coordinator for Health Information Technology, Washington, DC. Available at: https://www.healthit.gov/sites/default/files/nlc_shared_decision_making_fact_sheet.pdf (last accessed April 2024).
- Heaney, D.E., Norvill, A.J., 2006. A comparison of reduction in CT dose through the use of gantry angulations or bismuth shields. *Australas. Phys. Eng. Sci. Med.* 29, 172–178.
- Herrmann, T.L., Fauber, T.L., Gill, J., et al., 2012. Best practices in digital radiography. *Radiol. Technol.* 84, 83–89.
- Hiles, P., Sullivan, Y., Benson, E., et al., 2020. Guidance on Using Shielding on Patients for Diagnostic Radiology Applications. British Institute of Radiology, London.
- Hiles, P., Gilligan, P., Damilakis, J., et al., 2021. European consensus on patient contact shielding. *Insights Imag.* 12, 194.
- Hoang, J.K., Yoshizumi, T.T., Choudhury, K.R., et al., 2012. Organ based dose current modulation and thyroid shields: techniques of radiation dose reduction for neck CT. *AJR Am. J. Roentgenol.* 198, 1132–1138.
- Hoeffner, E.G., Case, I., Jain, R., et al., 2004. Cerebral perfusion CT: technique and clinical applications. *Radiology* 231, 632–644.
- Hsieh, J., Flohr, T., 2021. Computed tomography recent history and future perspectives. *J. Med. Imaging (Bellingham)* 8, 052109.
- Husmann, L., Valenta, I., Gaemperli, O., et al., 2008. Feasibility of low-dose coronary CT angiography: first experience with prospective ECG-gating. *Eur. Heart J.* 29, 191–197.
- IAEA, 2005. Optimization of the Radiological Protection of Patients: Image Quality and Dose in Mammography (Coordinated Research in Europe). IAEA TECDOC 1447. International Atomic Energy Agency, Vienna.
- IAEA, 2007. Dosimetry in Diagnostic Radiology: an International Code of Practice. Technical Reports Series No. 457. International Atomic Energy Agency, Vienna.
- IAEA, 2010. Patient Dose Optimization in Fluoroscopically Guided Interventional Procedures: Final Report of a Coordinated Research Project. IAEA TECDOC 1641. International Atomic Energy Agency, Vienna.
- IAEA, 2011. Avoidance of Unnecessary Dose to Patients While Transitioning from Analogue to Digital Radiology. IAEA-TECDOC-1667. International Atomic Energy Agency, Vienna.
- IAEA/WHO, 2012. Radiation Protection in Medicine: Setting the Scene for the Next Decade. Proc. Int. Conf. 3–7 December 2012, Bonn, Germany. Available at: https://rpop.iaea.org/RPOP/RPoP/Content/AdditionalResources/Bonn_Call_for_Action_Platform/ (last accessed January 2022).
- IAEA, 2015. Worldwide Implementation of Digital Imaging in Radiology. IAEA Human Health Series No. 28. International Atomic Energy Agency, Vienna.
- IAEA, 2020. Radiation Protection of Patients (RPOP). International Atomic Energy Agency, Vienna. Available at: <https://www.iaea.org/resources/rpop> (last accessed August 2022).

- IAEA, 2021. Implementation of a Remote and Automated Quality Control Programme for Radiography and Mammography Equipment. IAEA Human Health Series No. 39. International Atomic Energy Agency, Vienna. Available at: <https://www.iaea.org/publications/13539/implementation-of-a-remote-and-automated-quality-control-programme-for-radiography-and-mammography-equipment> (last accessed March 2024).
- IAEA, 2022a. Children and Radiation – What Patients Need to Know. Radiation Protection of Patients. International Atomic Energy Agency, Vienna. Available at: <https://www.iaea.org/resources/rpop/patients-and-public/children> (last accessed January 2022).
- IAEA, 2022b. Trigger Levels for Follow-up of Patients to Detect Clinically Relevant Tissue Reactions. International Atomic Energy Agency, Vienna. Available at: https://www.iaea.org/sites/default/files/22/06/trigger_levels_2022.pdf (last accessed August 2023).
- IAEA, 2022c. Radiation Protection in Dental Radiology. IAEA Safety Report Series No. 108. International Atomic Energy Agency, Vienna. Available at <https://www.iaea.org/publications/14720/radiation-protection-in-dental-radiology> (last accessed March 2024).
- IAEA, 2023a. Worldwide Implementation of Digital Mammography Imaging. IAEA Human Health Series No. 46. International Atomic Energy Agency, Vienna. Available at: <https://www.iaea.org/publications/15178/worldwide-implementation-of-digital-mammography-imaging> (last accessed March 2024).
- IAEA, 2023b. Handbook of Basic Quality Control Tests for Diagnostic Radiology. IAEA Human Health Series No. 47. International Atomic Energy Agency, Vienna. Available at: <https://www.iaea.org/publications/14890/handbook-of-basic-quality-control-tests-for-diagnostic-radiology> (last accessed August 2023).
- IAEA, 2023c. Patient Radiation Exposure Monitoring in Medical Imaging. Safety Report Series No. 112. International Atomic Energy Agency, Vienna. Available at: <https://www.iaea.org/publications/14971/patient-radiation-exposure-monitoring-in-medical-imaging> (last accessed August 2023).
- IAEA, 2023d. Safety in Radiological Procedures. International Atomic Energy Agency, Vienna. Available at: <https://www.iaea.org/resources/rpop/resources/databases-and-learning-systems/safrad> (last accessed August 2023).
- Ichimoto, E., Kadohira, T., Nakayama, T., De Gregorio, J. 2018. Efficacy of radiation dose reduction due to real-time monitoring and visualization of peak skin dose during coronary angiography and percutaneous coronary intervention. *Catheter. Cardiovasc. Interv.* 91, 717–722.
- ICRP, 1991. 1990 Recommendations of the International Commission on Radiological Protection. ICRP Publication 60. Ann. ICRP 21(1–3).
- ICRP, 1996. Radiological protection and safety in medicine. ICRP Publication 73. Ann. ICRP 26(2).
- ICRP, 2000a. Pregnancy and medical radiation. ICRP Publication 84. Ann. ICRP 30(1).
- ICRP, 2000b. Avoidance of radiation injuries from interventional procedures. ICRP Publication 85. Ann. ICRP 30(2).
- ICRP, 2000c. Managing patient dose in computed tomography. ICRP Publication 87. Ann. ICRP 30(4).
- ICRP, 2004. Managing patient dose in digital radiology. ICRP Publication 93. Ann. ICRP 34(1).
- ICRP, 2006. The optimisation of radiological protection: broadening the process. ICRP Publication 101b. Ann. ICRP 36(3).
- ICRP, 2007a. Managing patient dose in multi-detector computed tomography (MDCT). ICRP Publication 102. Ann. ICRP 37(1).

- ICRP, 2007b. The 2007 Recommendations of the International Commission on Radiological Protection. ICRP Publication 103. Ann. ICRP 37(2–4).
- ICRP, 2009. Education and training in radiological protection for diagnostic and interventional procedures. ICRP Publication 113. Ann. ICRP 39(5).
- ICRP, 2010. Radiological protection in fluoroscopically guided procedures performed outside the imaging department. ICRP Publication 117. Ann. ICRP 40(6).
- ICRP, 2012. ICRP statement on tissue reactions/early and late effects of radiation in normal tissues and organs – threshold doses for tissue reactions in a radiation protection context. ICRP Publication 118. Ann. ICRP 41(1/2).
- ICRP, 2013a. Radiological protection in cardiology. ICRP Publication 120. Ann. ICRP 42(1).
- ICRP, 2013b. Radiological protection in paediatric diagnostic and interventional radiology. ICRP Publication 121. Ann. ICRP 42(2).
- ICRP, 2015. Radiological protection in cone beam computed tomography (CBCT). ICRP Publication 129. Ann. ICRP 44(21).
- ICRP, 2017. Diagnostic reference levels in medical imaging. ICRP Publication 135. Ann. ICRP 46(1).
- ICRP, 2018a. Ethical foundations of the system of radiological protection. ICRP Publication 138. Ann. ICRP 47(1).
- ICRP, 2018b. Occupational radiological protection in interventional procedures. ICRP Publication 139. Ann. ICRP 47(2).
- ICRP, 2023. Optimisation of radiological protection in digital radiology techniques for medical imaging. ICRP Publication 154. Ann. ICRP 52(3).
- ICRP, 2024. Radiological protection in PET and PET/CT. In press.
- ICRPædia, 2024. ICRPædia. International Commission on Radiological Protection, Ottawa. Available at: http://icrpaedia.org/Main_Page (last accessed February 2024).
- ICRU, 2012. Radiation Dose and Image-quality Assessment in Computed Tomography. ICRU Report 87. International Commission on Radiation Units and Measurements, Bethesda, MD.
- IEC, 2008. Medical Electrical Equipment – Exposure Index of Digital X-ray Imaging Systems – Part 1: Definitions and Requirements for General Radiography. IEC 62494-1. International Electrotechnical Commission, Geneva.
- IEC, 2020. Medical Electrical Equipment – Part 2-43: Particular Requirements for the Basic Safety and Essential Performance of X-ray Equipment for Interventional Procedures. EN60601-2-43:2010/A2:2020(AMENDMENT). International Electrotechnical Commission, Geneva.
- IEC, 2022a. Medical Electrical Equipment – part 2-43: Particular Requirements for the Safety of X-Ray Equipment for Interventional Procedures. IEC 60601-2-43:2022 Edition 3.0. International Electrotechnical Commission, Geneva.
- IEC, 2022b. Medical Electrical Equipment – Part 2-54: Particular Requirements for the Basic Safety and Essential Performance of X-ray Equipment for Radiography and Radioscopy. Report 60601-2-54: 2022 RVL Edition 2.0. International Electrotechnical Commission, Geneva.
- Image Gently, 2022a. Digital Radiography. Stanford, CA. Available at: <https://www.imagegently.org/Procedures/Digital-Radiography> (last accessed January 2022).
- Image Gently, 2022b. Fluoroscopy Module. Stanford, CA. Available at: <https://www.imagegently.org/Procedures/Fluoroscopy/Pause-and-Pulse-Resources> (last accessed January 2022).

- Image Gently, 2022c. Step Lightly Checklist. Stanford, CA. Available at: https://www.imagegently.org/Portals/6/Procedures/ImGen_StpLight_Chcklst.pdf (last accessed January 2022).
- Image Gently, 2022d. CT Module. Stanford, CA. Available at: <https://www.imagegently.org/Procedures/Computed-Tomography> (last accessed January 2022).
- Image Gently, 2022e. Frequently Asked Questions – Fluoroscopy – Parents. Stanford, CA. Available at: <https://www.imagegently.org/Roles-What-can-I-do/Parent/Fluoroscopy> (last accessed January 2024).
- Image Gently, 2023. Image Gently Development of Pediatric CT Protocols 2014. Stanford, CA. Available at: <https://www.imagegently.org/Portals/6/Procedures/IG%20CT%20Protocols%20111714.pdf> (last accessed March 2023).
- Image Gently, 2024. Image Gently. Stanford, CA. Available at: <https://www.imagegently.org> (last accessed April 2024).
- Image Wisely, 2022a. Radiation Safety Cases. American College of Radiology, Reston, VA. Available at: <https://www.imagewisely.org/Educational-Tools/Radiation-Safety-Cases> (last accessed January 2022).
- Image Wisely, 2022b. CT Protocol Design. American College of Radiology, Reston, VA. Available at: <https://www.imagewisely.org/Imaging-Modalities/Computed-Tomography/Protocol-Design> (last accessed August 2022).
- Image Wisely, 2022c. Imaging Modalities and Educational Tools. American College of Radiology, Reston, VA. Available at: <https://www.imagewisely.org> (last accessed August 2022).
- Imanishi, Y., Fukui, A., Niimi, H., et al., 2005. Radiation-induced temporary hair loss as a radiation damage only occurring in patients who had the combination of MDCT and DSA. *Eur. Radiol.* 15, 41–46.
- Inkinen, S.I., Mäkelä, T., Kaasalainen, T., Peltonen, J., Kangasniemi, M., Kortetniemi, M., 2022. Automatic head computed tomography image noise quantification with deep learning. *Phys. Med.* 99, 102–112.
- IPEM, 2005. Recommended Standards for the Routine Performance Testing of Diagnostic X-ray Imaging Systems. Report 91. Institute of Physics and Engineering in Medicine, York.
- IPEM, 2010. Measurement of the Performance Characteristics of Diagnostic X-ray Systems. Digital Imaging Systems. IPEM Report 32, Part VII. Institute of Physics and Engineering in Medicine, York.
- IPEM, 2021. Dynamic X-Ray Imaging Systems Used in Medicine: Quality control in performance characteristics. IPEM Report 32, Part VIII, The Institute of Physics and Engineering in Medicine, York.
- Itatani, R., Oda, S., Utsunomiya, D., et al., 2013. Reduction in radiation and contrast medium dose via optimization of low-kilovoltage CT protocols using a hybrid iterative reconstruction algorithm at 256-slice body CT: phantom study and clinical correlation. *Clin. Radiol.* 68, e128–e135.
- Jamil, A., Mohd, M.I., Zain, N.M., 2018. The consistency of exposure indicator values in digital radiography systems. *Radiat. Prot. Dosimetry* 182, 413–418.
- Jaschke, W., Schmuth, M., Trianni, A., Bartal, G., 2017. Radiation-induced skin injuries to patients: what the interventional radiologist needs to know. *Cardiovasc. Intervent. Radiol.* 40, 1131–1140.

- Jaschke, W., Bartal, G., Martin, C.J., Vañó, E., 2020. Unintended and accidental exposures, significant dose events and trigger levels in interventional radiology. *Cardiovasc. Intervent. Radiol.* 43, 1114–1121.
- Johnson, P.B., Borrego, D., Balter, S., Johnson, K., Siragusa, D., Bolch, W.E., 2011. Skin dose mapping for fluoroscopically guided interventions. *Med. Phys.* 38, 5490–5499.
- Johnson, T.R.C., Krauss, B., Sedlmair, M., et al., 2007. Material differentiation by dual energy CT: initial experience. *Eur. Radiol.* 17, 1510–1517.
- Jones, A.K., Pasciak, A.S., 2011. Calculating the peak skin dose resulting from fluoroscopically guided interventions. Part I: Methods. *J. Appl. Clin. Med. Phys.* 12, 3670.
- Jones, A.K., Pasciak, A.S., 2012. Calculating the peak skin dose resulting from fluoroscopically-guided interventions. Part II: case studies. *J. Appl. Clin. Med. Phys.* 13, 3693.
- Jones, A.K., Balter, S., Rauch, P., Wagner, L.K., 2014. Medical imaging using ionizing radiation: optimization of dose and image quality in fluoroscopy. *Med. Phys.* 41, 014301.
- Jones, A.K., Heintz, P., Geiser, W., et al., 2015. Ongoing quality control in digital radiography: Report of AAPM Imaging Physics Committee Task Group 151. *Med. Phys.* 42, 6658–6670.
- Kaasalainen, T., Mäkelä, T., Kortensniemi, M., 2019. The effect of vertical centering and scout direction on automatic tube voltage selection in chest CT: a preliminary phantom study on two different CT equipments. *Eur. J. Radiol. Open* 6, 24–32.
- Kalender, W.A., Kolditz, D., Steiding, C., et al., 2017. Technical feasibility proof for high-resolution low-dose photon-counting CT of the breast. *Eur. Radiol.* 27, 1081–1086.
- Kalra, M., Maher, M., Toth, T., et al., 2004. Techniques and applications of automatic tube current modulation for CT. *Radiology* 233, 649–657.
- Kanal, K.M., Butler, P.F., Sengupta, D., Bhargavan-Chatfield, M., Coombs, L.P., Morin, R. L., 2017. U.S. diagnostic reference levels and achievable doses for 10 adult CT examinations. *Radiology* 284, 120–133.
- Kanal, K.M., Butler, P.F., Chatfield, M.B., et al., 2022. U.S. diagnostic reference levels and achievable doses for 10 pediatric CT examinations. *Radiology* 302, 164–174.
- Keefe, N.A., Haskal, Z.J., Park, A.W., Angle, J.F., 2018. *IR Playbook: a Comprehensive Introduction to Interventional Radiology*. Springer, Cham.
- Kim, Y.K., Sung, Y.M., Choi, J.H., Kim, E.Y., Kim, H.S., 2013. Reduced radiation exposure of the female breast during low-dose chest CT using organ-based tube current modulation and a bismuth shield: comparison of image quality and radiation dose. *AJR Am. J. Roentgenol.* 200, 537–544.
- Ko, S.M., Kim, T.H., Chun, E.J., Kim, J.Y., Hwang, S.H., 2019. Assessment of left ventricular myocardial diseases with cardiac computed tomography. *Korean J. Radiol.* 20, 333–351.
- Kleinman, P., Strauss, K., Zurakowski, D., Buckley, K.S., Taylor, G.A., 2010. Patient size measured on CT images as a function of age at a tertiary children’s hospital. *AJR Am. J. Roentgenol.* 194, 1611–1619.
- Kok, M., Muhl, C., Mingels, A.A., et al., 2014. Influence of contrast media viscosity and temperature on injection pressure in computed tomographic angiography: a phantom study. *Invest. Radiol.* 49, 217–223.
- Kotiahio, A., Manninen, A.-L., Nikkinen, J., Nieminen, M.T., 2018. Comparison of organ-based tube current modulation and bismuth shielding in chest CT. *Rad. Prot. Dosimetry* 185, 42–48.

- Kwan, M.L., Miglioretti, D.L., Marlow, E.C., et al., 2019. Trends in medical imaging during pregnancy in the United States and Ontario, Canada, 1996 to 2016. *JAMA Netw. Open* 2, e197249.
- Lambert, J.W., Gould, R.G., 2016. Evaluation of a net dose-reducing organ-based tube current modulation technique: comparison with standard dose and bismuth-shielded acquisitions. *AJR Am. J. Roentgenol.* 206, 1233–1240.
- Lazarus, E., Debenedictis, C., North, D., et al., 2009. Utilization of imaging in pregnant patients: 10-year review of 5270 examinations in 3285 patients 1997–2006. *Radiology* 251, 517–524.
- Lee, C., Lodwick, D., Hurtado, J., Pafundi, D., Williams, J.L., Bolch, W.E., 2010. The UF family of reference hybrid phantoms for computational radiation dosimetry. *Phys. Med. Biol.* 55, 339–363.
- Lee, C., Goo, J., Ye, H., et al., 2008. Radiation dose modulation techniques in the multi-detector CT era: from basics to practice. *Radiographics* 28, 1451–1459.
- Leipsic, J., Nguyen, G., Brown, J., Sin, D., Mayo, J.R., 2010. A prospective evaluation of dose reduction and image quality in chest CT using adaptive statistical iterative reconstruction. *AJR Am. J. Roentgenol.* 195, 1095–1099.
- Lell, M.M., Kachelriess, M., 2020. Recent and upcoming technological developments in computed tomography. *Invest. Radiol.* 55, 8–19.
- Leung, A.N., Bull, T.M., Jaeschke, R., et al., 2012. American Thoracic Society documents: an official American Thoracic Society/Society of Thoracic Radiology Clinical Practice Guideline – Evaluation of suspected pulmonary embolism in pregnancy. *Radiology* 262, 635–646.
- Lin, P.J.P., Schueler, B.A., Balter, S., et al., 2015. Accuracy and calibration of integrated radiation output indicators in diagnostic radiology: a report of the AAPM Imaging Physics Committee Task Group 190. *Med. Phys.* 42, 6773–7202.
- Lin, P.J.P., Goode, A.R., Corwin, F.D., et al., 2022. AAPM Task Group Report 272: Comprehensive acceptance testing and evaluation of fluoroscopy imaging systems. *Med. Phys.* 49, e1–e49.
- Longo, M., Genovese, E., Orlandi, C., et al., 2017. A novel method for CT dosimetry with a suspended phantom setup. *Phys. Med.* 40, 122–129.
- Mahesh, M., 2001. Fluoroscopy: patient radiation exposure issues. *Radiographics* 21, 1033–1045.
- Mahesh, M., 2016. What is the CT dose check standard, and why do CT scanners need to be in compliance? *J. Am. Coll. Radiol.* 13, 64–66.
- Mahesh, M., Hevezi, J.M., 2010. Features to consider when selecting a new CT scanner. *J. Am. Coll. Radiol.* 7, 820–822.
- Maier, J., Eulig, E., Vöth, T., et al., 2019. Real-time scatter estimation for medical CT using the deep scatter estimation: method and robustness analysis with respect to different anatomies, dose levels, tube voltages, and data truncation. *Med. Phys.* 46, 238–249.
- Maier, J., Klein, L., Eulig, E., Sawall, S., Kachelrieß, M., 2022. Real-time estimation of patient-specific dose distributions for medical CT using the deep dose estimation. *Med. Phys.* 49, 2259–2269.
- Manava, P., Galster, M., Ammon, J., Singer, J., Lell, M.M., Rieger, V., 2023. Optimized camera-based patient positioning in CT: impact on radiation exposure. *Invest. Radiol.* 58, 126–130.
- Malchair, F., Dabin, J., Deleu, M., Maccia, C., Merce, M.S., 2018. D 9.141 – Standards for Digital Dose Reporting. VERIDIC Project. European Joint Programme for the Integration of Radiation Protection Research, Brussels.

- Malik, R.F., Buljac-Samardžić, M., Akdemir, N., Hilders, C., Scheele, F., 2020. What do we really assess with organisational culture tools in healthcare? An interpretive systematic umbrella review of tools in healthcare. *BMJ Open Qual.* 9, e000826.
- Marin, D., Nelson, R.C., Samei, E., et al., 2009. Hypervascular liver tumors: low tube voltage, high tube current multidetector CT during late hepatic arterial phase for detection—initial clinical experience. *Radiology* 251(3), 771–779.
- Marsh, R.M., Silosky, M., 2019. Patient shielding in diagnostic imaging: discontinuing a legacy practice. *AJR Am. J. Roentgenol.* 212, 755–757.
- Martin, C.J., 2007. The importance of radiation quality for optimisation in radiology. *Biomed. Imaging Interv. J.* 3, e38.
- Martin, C.J., Huda, W., 2013. Intercomparison of patient CTDI surveys in three countries. *Radiat. Prot. Dosimetry* 153, 431–440.
- Martin, C.J., Sookpeng, S., 2016. Setting up computed tomography automatic tube current modulation systems. *J. Radiol. Prot.* 36, R74–R95.
- Martin, C.J., Vassileva, J., Vañó, E., et al., 2017. Unintended and accidental medical radiation exposures in radiology: guidelines on investigation and prevention. *J. Radiol. Prot.* 37, 883–906.
- Matsubara, K., Koshida, K., Ichikawa, K., et al., 2009. Misoperation of CT automatic tube current modulation systems with inappropriate patient centring: phantom studies. *AJR Am. J. Roentgenol.* 129, 862–865.
- Matsunaga, Y., Chida, K., Kondo, Y., et al., 2019. Diagnostic reference levels and achievable doses for common computed tomography examinations: results from the Japanese nationwide dose survey. *Br. J. Radiol.* 91, 20180290.
- Maués, N.H.P.B., Alves, A.F.F., Pavan, A.L.M., et al., 2018. Abdomen-pelvis computed tomography protocol optimization: an image quality and dose assessment. *Radiat. Prot. Dosimetry* 184, 66–72.
- Mayer, C., Meyer, M., Fink, C., et al., 2014. Potential for radiation dose savings in abdominal and chest CT using automatic tube voltage selection in combination with automatic tube current modulation. *AJR Am. J. Roentgenol.* 203, 292–299.
- Mayo-Smith, W.W., Hara, A.K., Mahesh, M., Sahani, D.V., Pavlicek, W., 2014. How I do it: managing radiation dose in CT. *Radiology* 273, 657–672.
- McCabe, B.P., Speidel, M.A., Pike, T.L., Van Lysel, M.S., 2011. Calibration of GafChromic XR-RV3 radiochromic film for skin dose measurement using standardized x-ray spectra and a commercial flatbed scanner. *Med. Phys.* 38, 1919–1930.
- McCollough, C.H., Zink, F.E., Kofler, J.M., et al., 2002. Dose optimisation in CT: creation, implementation and clinical acceptance of size-based technique charts. *Radiology* 225, 591.
- McCollough, C.H., Bruesewitz, M.R., Kofler, J.M., 2006. CT dose reduction and dose management tools: overview of available options. *Radiographics* 26, 503–512.
- McCollough, C.H., Schueler, B.A., Atwell, T.D., et al., 2007. Radiation exposure and pregnancy: when should we be concerned? *Radiographics* 27, 909–918.
- McCollough, C.H., Leng, S., Yu, L., Fletcher, J.G., 2015. Dual- and multi-energy CT: principles, technical approaches, and clinical applications. *Radiology* 276, 637–653.
- McCollough, C.H., Boedeker, K., Cody, D., et al., 2020. Principles and applications of multi-energy CT: report of AAPM Task Group 291. *Med. Phys.* 47, e881.
- McCullough, C.H., Leng, S., 2019. Use of artificial intelligence in computed tomography dose optimisation. *Ann. ICRP* 49(S1), 113–125.

- McCollough, C.H., Rajiah, P.S., 2023. Milestones in CT: past, present, and future. *Radiology* 309, e230803.
- McFadden, S., Roding, T., de Vries, G., et al., 2018. Digital imaging and radiographic practise in diagnostic radiography: an overview of current knowledge and practice in Europe. *Radiography* 24, 137–141.
- McKenney, S.E., Seibert, J.A., Lamba, R., Boone, J.M., 2014. Methods for CT automatic exposure control protocol translation between scanner platforms. *J. Am. Coll. Radiol.* 11, 285–291.
- Mello-Amoedo, C.D., Martins, A.N., Tachibana, A., Pinho, D.F., Baroni, R.H., 2018. Comparison of radiation dose and image quality of abdominopelvic CT using iterative (AIDR 3D) and conventional reconstructions. *AJR Am. J. Roentgenol.* 210, 127–133.
- Mentrup, D., Neitzel, U., Jocke, S., Maack, H-I., Menser, B., 2014. Grid-like Contrast Enhancement for Bedside Chest Radiographs Acquired Without Anti-scatter Grid. Philips, Amsterdam.
- Merzan, D., Nowik, P., Poludniowski, G., Bujila, R., 2017. Evaluating the impact of scan settings on automatic tube current modulation in CT using a novel phantom. *Br. J. Radiol.* 90, 20160308.
- Mettler, F.A., Thomadsen, B.R., Bhargavan, M., et al., 2008. Medical radiation exposure in the US in 2006: preliminary results. *Health Phys.* 95, 502–507.
- Mohammadinejad, P., Mileto, A., Yu, L., et al., 2021. CT noise-reduction methods for lower-dose scanning: strengths and weaknesses of iterative reconstruction algorithms and new techniques. *Radiographics* 41, 1493–1508.
- Montalescot, G., Sechtem, U., Achenbach, S., et al., 2013. ESC guidelines on the management of stable coronary artery disease: the Task Force on the Management of Stable Coronary Artery Disease of the European Society of Cardiology. *Eur. Heart J.* 34, 2949–3003.
- Morimoto, L.N., Kamaya, A., Boulay-Coletta, I., et al., 2017. Reduced dose CT with model-based iterative reconstruction compared to standard dose CT of the chest, abdomen, and pelvis in oncology patients: intra-individual comparison study on image quality and lesion conspicuity. *Abdom. Radiol.* 42, 2279–2288.
- Moore, C.S., Wood, T.J., Avery, G., et al., 2014. An investigation of automatic exposure control calibration for chest imaging with a computed radiography system. *Phys. Med. Biol.* 59, 2307–2324.
- Moore, C.S., Wood, T.J., Avery, G., et al., 2016. Automatic exposure control calibration and optimisation for abdomen, pelvis and spine imaging with a computed radiography system. *Phys. Med. Biol.* 61, N551.
- Moore, C.S., Wood, T.J., Jones, S., Saunderson, J.R., Beavis, A.W., 2019. A practical method to calibrate and optimise automatic exposure control devices for computed radiography (CR) and digital radiography (DR) imaging systems using the signal-to-noise ratio (SNR) metric. *Biomed. Phys. Eng. Express* 5, 035027.
- Morrison, G., John, S.D., Goske, M.J., et al., 2011. Pediatric digital radiography education for radiologic technologists: current state. *Pediatr. Radiol.* 41, 602–610.
- Mortensen, K.H., Tann, O., 2018. Computed tomography in paediatric heart disease. *Br. J. Radiol.* 91, 20180201.
- Mulkens, T.H., Bellinck, P., Baeyaert, M., et al., 2005. Use of an automated exposure control mechanism for dose optimization in multi-detector row CT examinations: clinical evaluation. *Radiology* 237, 213–223.

- Nagayama, Y., Sakabe, D., Goto, M., 2021. Deep learning-based reconstruction for lower-dose pediatric CT: technical principles, image characteristics, and clinical implementations. *Radiographics* 41, 1936–1953.
- Nam, J.G., Ahn, C., Choi, H., et al., 2021. Image quality of ultralow-dose chest CT using deep learning techniques: potential superiority of vendor-agnostic post-processing over vendor-specific techniques. *Eur. Radiol.* 31, 5139–5147.
- NCRP, 2010. Radiation Dose Management for Fluoroscopically-guided Interventional Medical Procedures. NCRP Report 168. National Council on Radiation Protection and Measurements, Bethesda, MD.
- NCRP, 2019a. Radiation Protection in Dentistry and Oral & Maxillofacial Imaging. NCRP Report No. 177. National Council on Radiation Protection and Measurements, Bethesda, MD.
- NCRP, 2019b. Medical Exposure of Patients in the United States. NCRP Report No. 184. National Council on Radiation Protection and Measurements, Bethesda, MD.
- NCRP, 2021. NCRP Recommendations for Ending Routine Gonadal Shielding During Abdominal and Pelvic Radiography. NCRP Statement No. 13. National Council on Radiation Protection and Measurements, Bethesda, MD.
- NCRP, 2023. Recommendations for Stratification of Equipment Use and Radiation Safety Training for Fluoroscopy. NCRP Commentary No. 33. National Council on Radiation Protection and Measurements, Bethesda, MD.
- Neil, S., Padgham, C., Martin, C.J., 2010. A study of the relationship between peak skin dose and cumulative air kerma in interventional neuroradiology and cardiology. *J. Radiol. Prot.* 30, 659–672.
- NEMA, 2013. Standard Attributes on CT Equipment Related to Dose Optimization and Management. NEMA Standards Publication XR 29-2013. National Electrical Manufacturers Association, Rosslyn, VA. Available at: <https://nema.org/Standards/Pages/Standard-Attributes-on-CT-Equipment-Related-to-Dose-Optimization-and-Management.aspx#download> (last accessed April 2017).
- NEMA, 2016. Standard Attributes on X-ray Equipment for Interventional Procedures. NEMA Standards Publication XR 31-2016. National Electrical Manufacturers Association, Rosslyn, VA.
- NEMA, 2018. X-ray Equipment for Interventional Procedures User Quality Control Mode. NEMA Standards Publication XR 27-2013. National Electrical Manufacturers Association, Rosslyn, VA.
- Nikupaavo, U., Kaasalainen, T., Reijonen, V., 2015. Lens dose in routine head CT: comparison of different optimization methods with anthropomorphic phantoms. *AJR Am. J. Roentgenol.* 204, 117–123.
- Ota, J., Yokota, H., Takishima, H., et al., 2019. Breast exposure reduction using organ-effective modulation on chest CT in Asian women. *Eur. J. Radiol.* 119, 108651.
- Papadakis, A.E., Damilakis, J., 2020. Evaluation of an organ-based tube current modulation tool in pediatric CT examinations. *Eur. Radiol.* 30, 5728–5737.
- Pasquino, M., Cutaia, C., Poli, M., et al., 2018. Patient's peak skin dose evaluation using Gafchromic films in interventional cardiology procedures and its correlation with other dose indicators. *Phys. Med.* 53, 103–107.
- Persson, M., Bujila, R., Nowik, P., et al., 2016. Upper limits of the photon fluence rate on CT detectors: case study on a commercial scanner. *Med. Phys.* 43, 4398–4411.

- Prakash, P., Kalra, M.K., Kambadakone, A., et al., 2010. Reducing abdominal CT radiation dose with adaptive statistical iterative reconstruction technique. *Invest. Radiol.* 45, 202–210.
- Queiroz, P.M., Santaella, G.M., de Castro Lopes, S.L.P., Haiter-Neto, F., Freitas, D.Q., 2020. Characteristics of radiographic images acquired with CdTe, CCD and CMOS detectors in skull radiography. *Imaging Sci. Dent.* 50, 339–346.
- Radvany, M.G., Mahesh, M., 2015. Last series hold: a feature on fluoroscopy systems with the potential to reduce patient and operator dose. *J. Am. Coll. Radiol.* 12, 860–861.
- Rajendran, K., Petersilka, M., Henning, A., et al., 2021a. Full field-of-view, high-resolution, photon-counting detector CT: technical assessment and initial patient experience. *Phys. Med. Biol.* 66, 205019.
- Rajendran, K., Petersilka, M., Henning, A., et al., 2021b. First clinical photon-counting detector CT system: technical evaluation. *Radiology* 303, 130–138.
- Rajagopal, J.R., Farhadi, F., Richards, T., et al., 2021. Evaluation of coronary plaques and stents with conventional and photon-counting CT: benefits of high-resolution photon-counting CT. *Radiol. Cardiothorac. Imaging* 3, e210102.
- Rampado, O., Marchisio, F., Izzo, A., et al., 2009. Effective dose and image quality evaluations of an automatic CT tube current modulation system with an anthropomorphic phantom. *Eur. J. Radiol.* 72, 181–187.
- Ranallo, F., 2013. CT protocol optimization over the range of CT scanners: recommendations and misconceptions. American Association of Physicists in Medicine, New York. Available at: <http://amos3.aapm.org/abstracts/pdf/77-22652-312436-91821.pdf> (last accessed August 2022).
- Ranallo, F.N., Szczykutowicz, T., 2015. The correct selection of pitch for optimal CT scanning: avoiding common misconceptions. *J. Am. Coll. Radiol.* 12, 423–424.
- Rana, V.K., Rudin, S., Bednarek, D.R., 2016. A tracking system to calculate patient skin dose in real-time during neurointerventional procedures using a biplane x-ray imaging system. *Med. Phys.* 43, 5131–5144.
- Ranschaert, E.R., Morozov, S., Algra, P.R., 2019. Artificial Intelligence in Medical Imaging: Opportunities, Applications and Risks. Springer, Cham.
- Raptis, C.A., Mellnick, V.M., Raptis, D.A., et al., 2014. Imaging of Trauma in the Pregnant Patient. *RadioGraphics* 34, 748–763.
- RCR, 2014. Standards of Practice of Computed Tomography Coronary Angiography in Adult Patients. Royal College of Radiologists, London. Available at: <http://www.rcr.ac.uk/> (last accessed August 2022).
- Rizzo, S., Kalra, M., Schmidt, B., et al., 2006. Comparison of angular and combined automatic tube current modulation techniques with constant tube current CT of the abdomen and pelvis. *AJR Am. J. Roentgenol.* 186, 673–679.
- Roehrig, H., Krupinski, E.A., Hulet, R., 1997. Reduction of patient exposure in pediatric radiology. *Acad. Radiol.* 4, 547–557.
- Rostad, B.S., Applegate, K.E., Kim, T., Mansour, R.M., Milla, S.S., 2018. Multiphase acquisitions in pediatric abdominal-pelvic CT are a common practice and contribute to unnecessary radiation dose. *Pediatr. Radiol.* 48, 1714–1723.
- Ruzsics, B., Gebregziabher, M., Lee, H., et al., 2009. Coronary CT angiography: automatic cardiac-phase selection for image reconstruction. *Eur. Radiol.* 19, 1906–1913.
- Sahiner, B., Pezeshk, A., Hadjiiski, L.M., et al., 2019. Deep learning in medical imaging and radiation therapy. *Med. Phys.* 46, e1–e36.

- Saltybaeva, N., Platon, A., Poletti, P-A., Hinzpeter, R., Merce, M.S., Alkadhi, H., 2020. Radiation dose to the fetus from computed tomography of pregnant patients – development and validation of a web-based tool. *Invest. Radiol.* 55, 762–768.
- Saltybaeva, N., Schmidt, B., Wimmer, A., Flohr, T., Alkadhi, H., 2018. Precise and automatic patient positioning in computed tomography: avatar modeling of the patient surface using a 3-dimensional camera. *Invest. Radiol.* 53, 641–646.
- Samara, E., Stratakis, J., Enele Melono, J.M., Mouzas, I.A., Perisinakis, K., Damilakis, J., 2009. Therapeutic ERCP and pregnancy: is the radiation risk for the embryo trivial? *Gastrointest. Endosc.* 69, 824–831.
- Samei, E., Dobbins, III J.T., Lo, J.Y., Tornai, M.P., 2005. A framework for optimising the radiographic technique in digital x-ray imaging. *Radiat. Prot. Dosimetry* 114, 220–229.
- Samei, E., Kruipinski, E., 2018. *The Handbook of Medical Image Perception and Techniques*, second ed. Cambridge University Press, New York.
- Samei, E., Järvinen, H., Kortensniemi, M., et al., 2018. Medical imaging dose optimisation from ground up: expert opinion of an international summit. *J. Radiol. Prot.* 38, 967–989.
- Schenzle, J.C., Sommer, W.H., Neumaier, K., et al., 2010. Dual energy CT of the chest: how about the dose? *Invest. Radiol.* 45, 347–353.
- Schindera, S.T., Odedra, D., Raza, S.A., et al., 2013. Iterative reconstruction algorithm for CT: can radiation dose be decreased while low-contrast detectability is preserved? *Radiology* 269, 511–518.
- Schmidt, B., Saltybaeva, N., Kolditz, D., Kalender, W.A., 2013. Assessment of patient dose from CT localizer radiographs. *Med. Phys.* 40, 084301.
- Schulz, B., Kuehling, K., Kromen, W., et al., 2012. Automatic bone removal technique in whole-body dual-energy CT angiography: performance and image quality. *AJR Am. J. Roentgenol.* 199, W646–W650.
- See, K.W., Chui, K.H., Chan, W.H., Wong, K.C., Chan, Y.C., 2016. Evidence for endovascular simulation training: a systematic review. *Eur. J. Vasc. Endovasc. Surg.* 51, 441–451.
- Seeram, E., 2019. *Digital Radiography: Physical Principles and Quality Control*, second ed. Springer Nature, Singapore.
- Shahir, K., McCrea, J.M., Lozano, L.A.S., Goodman, L.R., 2015. Reduced z-axis technique for CT pulmonary angiography in pregnancy – validation for practical use and dose reduction. *Emerg. Radiol.* 22, 651–656.
- Sheth, N.M., Zbijewski, W., Jacobson, M.W., et al., 2018. Mobile C-arm with a CMOS detector: technical assessment of fluoroscopy and cone-beam CT imaging performance. *Med. Phys.* 45, 5420–5436.
- Shields, E., Bushong, S.C., 2012. Beware the mask. *J. Am. Coll. Radiol.* 10, 149–152.
- Shrimpton, P.C., Hillier, M.C., Meeson, S., Golding, S.J., 2014. Doses from Computed Tomography (CT) Examinations in the UK – 2011 Review. PHE-CRCE-013. Public Health England, Chilton.
- Singh, R., Wu, W., Wang, G., et al., 2020. Artificial intelligence in image reconstruction: the change is here. *Phys. Med.* 79, 113–125.
- Smith-Bindman, R., Wang, Y., Chu, P., et al., 2019. International variation in radiation dose for computed tomography examinations: prospective cohort study. *BMJ* 364, k4931.
- Siegel, M.J., Ramirez-Giraldo, J.C., 2019. Dual-energy CT in children: imaging algorithms and clinical applications. *Radiology* 291, 286–297.
- Söderberg, M., 2016. Overview, practical tips and potential pitfalls of using automatic exposure control in CT: Siemens Care Dose 4D. *Radiat. Prot. Dosimetry* 169, 84–91.

- Söderberg, M., Gunnarsson, M., 2010. Automatic exposure control in computed tomography – an evaluation of systems from different manufacturers. *Acta Radiol.* 51, 625–634.
- Sodickson, A.D., Keraliya, A., Czakowski, B., Primak, A., Wortman, J., Uyeda, J.W., 2021. Dual energy CT in clinical routine: how it works and how it adds value. *Emerg. Radiol.* 28, 103–117.
- Solomou, G., Papadakis, A.E., Damilakis, J., 2015. Abdominal CT during pregnancy: a phantom study on the effect of patient centring on conceptus radiation dose and image quality. *Eur. Radiol.* 25, 911–921.
- Solomou, G., Perisinakis, K., Tsetis, D., Stratakis, J., Damilakis, J., 2016. Data and methods to estimate fetal dose from fluoroscopically guided prophylactic hypogastric artery balloon occlusion. *Med. Phys.* 43, 2990–2997.
- Somasundaram, E., Brady, S.L., Strauss, K.J., 2022. Application of reference air kerma alert levels for paediatric fluoroscopic examinations. *J. Appl. Clin. Med. Phys.* 23, e13721.
- Sookpeng, S., Martin, C.J., Cheebsumon, P., Pengpan, T., 2017. Practical experiences in the transfer of clinical protocols between CT scanners with different ATCM systems. *J. Radiol. Prot.* 37, 84–96.
- Sookpeng, S., Martin, C.J., Gentle, D.J., 2013. Comparison of different phantom designs for CT scanner automatic tube current modulation system tests. *J. Radiol. Prot.* 33, 735–761.
- Sookpeng, S., Martin, C.J., Gentle, D.J., 2015. Investigation of the influence of image reconstruction filter and scan parameters on operation of automatic tube current modulation systems for different CT scanners. *Radiat. Prot. Dosimetry* 163, 521–530.
- Sookpeng, S., Martin, C.J., Gentle, D.J., Lopez-Gonzalez, M.R., 2014. Relationships between patient size, dose and image noise under automatic tube current modulation systems. *J. Radiol. Prot.* 34, 103–123.
- Sookpeng, S., Martin, C.J., Krisanachinda, A., 2020. Design and use of a phantom for testing and comparing the performance of computed tomography automatic tube current modulation systems. *J. Radiol. Prot.* 40, 753–773.
- SoR, 2023. Inclusive Pregnancy Status Guidelines for Ionising Radiation: Diagnostic and Therapeutic Exposures. Society of Radiographers, London. Available at: <https://www.sor.org/learning-advice/professional-body-guidance-and-publications/documents-and-publications/policy-guidance-document-library/inclusive-pregnancy-status-guidelines-for-ionising> (last accessed May 2023).
- SPR, 2008. Practice Quality Improvement Module for Performance of the Voiding Cystourethrogram. Society for Pediatric Radiology, Reston, VA. Available at: <https://www.pedrad.org/Portals/5/Education/PQI/PQI-VCUG%20Template.pdf> (last accessed January 2022).
- Stecker, M.S., Balter, S., Towbin, R.B., et al., 2009. Guidelines for patient radiation dose management. *J. Vasc. Interv. Radiol.* 20, S263–S273.
- Steffensen, C., Trypis, G., Mander, G.T.W., Munn, Z., 2021. Optimisation of radiographic acquisition parameters for direct digital radiography: a systematic review. *Radiography* 27, 663–672.
- Stevens, G., 2021. Dynamic X-ray Imaging Systems Used in Medicine – Quality Control in Performance Characteristics. IPEM TG Report 32 Part 8. IPEM-IOP Series in Physics and Engineering in Medicine. IOP Publishing, Bristol.
- Stratis, A., Kottou, S., Molfetas, M., et al., 2013. The effect of combined tube current modulation system on dose delivered to patients undergoing thoracic and abdominal CT with a 128-slice scanner. *Radiat. Prot. Dosimetry* 153, 206–211.

- Strauss, K.J., Goske, M.J., Kaste, S.C., et al., 2010. Image Gently: ten steps you can take to optimize image quality and lower CT dose for pediatric patients. *AJR Am. J. Roentgenol.* 194, 868–873.
- Sun, K., Han, R., Zhao, R., et al., 2018. Evaluation of dual energy computed tomography iodine mapping within the myocardial blood pool for detection of acute myocardial infarction: correlation with histopathological findings in a porcine model. *Br. J. Radiol.* 91, 20170569.
- Supanich, M.P., 2013. Tube current modulation. AAPM 3rd CT Dose Summit, Strategies for CT Scan Parameter Optimization, 15–16 March 2013, Phoenix, AZ, USA. Available at: www.aapm.org/meetings/2013CTS/documents/Fri_10SupanichTCMFinal.pdf (last accessed January 2016).
- Suzuki, K., 2017. Overview of deep learning in medical imaging. *Radiol. Phys. Technol.* 10, 257–273.
- Tabari, A., Gee1, M.S., Singh, R., 2020. Reducing radiation dose and contrast medium volume with application of dual-energy CT in children and young adults. *Am. J. Roentgenol.* 214, 1199–1205.
- Taguchi, N., Oda, S., Nakaura, T., et al., 2018. Contrast enhancement in abdominal computed tomography: influence of photon energy of different scanners. *Br. J. Radiol.* 91, 20170285.
- Taguchi, K., Iwanczyk, J.S., 2013. Vision 20/20: single photon counting x-ray detectors in medical imaging. *Med. Phys.* 40, 100901.
- Talei Franzesi, C.R., Ippolito, D., Riva, L., Fior, D., Cangiotti, C., Sironi, S., 2018. Diagnostic value of iterative reconstruction algorithm in low kV CT angiography (CTA) with low contrast medium volume for transcatheter aortic valve implantation (TAVI) planning: image quality and radiation dose exposure. *Br. J. Radiol.* 91, 20170802.
- Tan, S.K., Yeong, C.H., Raja Aman, R.R.A., et al., 2018. Low tube voltage prospectively ECG-triggered coronary CT angiography: a systematic review of image quality and radiation dose. *Br. J. Radiol.* 91, 20170874.
- Teeuwisse, W.M., Geleijns, J., Broerse, J.J., Obermann, W.R., van Persijn van Meerten, E.L., 2001. Patient and staff dose during CT guided biopsy, drainage and coagulation. *Br. J. Radiol.* 74, 720–726.
- Temsah, M.H., Al-Eyadhy, A., Alsohime, F., et al., 2021. Unintentional exposure and incidental findings during conventional chest radiography in the pediatric intensive care unit. *Medicine (Baltimore)* 100, e24760.
- Tsalafoutas, I.A., Tsapaki, V., Triantopoulou, C., Gorantonaki, A., Papailiou, J., 2007. CT-guided interventional procedures without CT fluoroscopy assistance: patient effective dose and absorbed dose considerations. *AJR Am. J. Roentgenol.* 188, 1479–1484.
- Tsalafoutas, I.A., Arlany, L., Titovich, E., et al., 2023. Technical specifications of dose management systems: An international atomic energy agency survey. *J. Appl. Clin. Med. Phys.* 25(1), e14219.
- Tzedakis, A., Damilakis, J., Perisinakis, K., Stratakis, J., Gourtsoyiannis, N., 2005. The effect of z-overscanning on patient effective dose from multi-detector spiral computed tomography examinations. *Med. Phys.* 32, 1621–1629.
- Uffmann, M., Schaefer-Prokop, C., 2009. Digital radiography: the balance between image quality and required radiation dose. *Eur. J. Radiol.* 72, 202–208.
- UNSCEAR, 2000. Sources and Effects of Ionizing Radiation. Volume I: Sources. Annex D. Medical Radiation Exposures. United Nations Scientific Committee on the Effects of Atomic Radiation, Vienna.

- UNSCEAR, 2008. Sources and Effects of Ionizing Radiation. Volume I: Sources. Annex A. Medical Radiation Exposures. United Nations Scientific Committee on the Effects of Atomic Radiation, Vienna.
- UNSCEAR, 2013. Sources and Effects of Ionizing Radiation. Volume II: Annex B – Effects of Radiation Exposure of Children. United Nations Scientific Committee on the Effects of Atomic Radiation, Vienna.
- UNSCEAR, 2022. Sources, Effects and Risks of Ionizing Radiation. Volume I: Annex A – Evaluation of Medical Exposure to Ionizing Radiation. United Nations Scientific Committee on the Effects of Atomic Radiation, Vienna.
- Vañó, E., Guibelalde, E., Fernandez, J.M., Gonzalez, L., Ten, J.I., 1997. Patient dosimetry in interventional radiology using slow films. *Br. J. Radiol.* 70, 195–200.
- Vañó, E., Gonzalez, L., Ten, J.I., Fernandez, J.M., Guibelalde, E., Macaya, C., 2001. Skin dose and dose-area product values for interventional cardiology procedures. *Br. J. Radiol.* 74, 48–55.
- Vañó, E., Fernández, J.M., Ten, J.I., Sanchez, R.M., 2022. Benefits and limitations for the use of radiation dose management systems in medical imaging. Practical experience in a university hospital. *Br. J. Radiol.* 95, 20211340.
- Van Straten, M., Venema, H.W., Majoie, C.B.L.M., et al., 2007. Image quality of multisection CT of the brain: thickly collimated sequential scanning versus thinly collimated spiral scanning with image combining. *AJNR Am. J. Neuroradiol.* 28, 421–427.
- Vassileva, J., Rehani, M., Kostova-Lefterova, D., et al., 2015. A study to establish international diagnostic reference levels for paediatric computed tomography. *Radiat. Prot. Dosimetry* 165, 70–80.
- Vassileva, J., Applegate, K.E., Paulo, G., Vañó, E., Holmberg, O.J., 2022. Strengthening radiation protection education and training of health professionals: conclusions from an IAEA meeting. *J. Radiol. Prot.* 42, 011504.
- Wall, B.F., Haylock, R., Jansen, J.T.M., et al., 2011. Radiation Risks from Medical X-ray Examinations as a Function of Age and Sex of Patient. HPA Report HPA-CRCE-028. Health Protection Agency, Chilton.
- Walsh, C., Gorman, D., Byrne, P., Larkin, A., Dowling, A., Malone, J.F., 2008. Quality assurance of computed and digital radiography systems. *Radiat. Prot. Dosimetry* 129, 271–275.
- Ward, V.L., Strauss, K.J., Barnewolt, C.E., et al., 2008. Paediatric radiation exposure and effective dose reduction during voiding cystourethrography. *Radiology* 249, 1002–1009.
- WFPI, 2022. The World Federation of Pediatric Imaging. Available at: <https://www.wfpiweb.org/> (last accessed January 2022).
- White, S.C., Pharoah, M.J., 2013. *Oral Radiology. Principles and Interpretation*, seventh ed. Elsevier-Mosby, St. Louis, MO.
- WHO, 2016. *Communicating Radiation Risk in Paediatric Imaging: Information to Support Healthcare Discussions About Benefit and Risk*. World Health Organization, Geneva. Available at: https://www.who.int/ionizing_radiation/pub_meet/radiation-risks-paediatric-imaging/en/ (last accessed July 2020).
- Willemink, M.J., de Jong, P.A., Leiner, T., et al., 2013a. Iterative reconstruction techniques for computed tomography part 1: technical principles. *Eur. Radiol.* 23, 1623–1631.
- Willemink, M.J., Leiner, T., de Jong, P.A., et al., 2013b. Iterative reconstruction techniques for computed tomography part 2: initial results in dose reduction and image quality. *Eur. Radiol.* 23, 1632–1642.

- Willis, C.E., Slovis, T.L., 2004. The ALARA concept in pediatric CR and DR: dose reduction in pediatric radiographic exams – a white paper conference executive summary. *Pediatr. Radiol.* 34, S162–S164.
- Wilson, S.M., Prasan, A.M., Viridi, A., et al., 2016. Real-time colour pictorial radiation monitoring during coronary angiography: effect on patient peak skin and total dose during coronary angiography. *EuroIntervention* 12, e939–e947.
- Wilson, J.M., Christianson, O.I., Richard, S., Samei, E., 2013. A methodology for image quality evaluation of advanced CT systems. *Med. Phys.* 40, 031908.
- Wiltling, J.E., Zwartkruis, A., van Leeuwen, M.S., Timmer, J., Kamphuis, A.G.A., Feldberg M., 2001. A rational approach to dose reduction in CT: individualized scan protocols. *Eur. Radiol.* 11, 2627–2632.
- Winklehner, A., Goetti, R., Baumueller, S., et al., 2011. Automated attenuation-based tube potential selection for thoracoabdominal computed tomography angiography: improved dose effectiveness. *Invest. Radiol.* 46, 767–773.
- Wood, T.J., Moore, C.S., Stephens, A., Saunderson, J.R., Beavis, A.W., 2015. A practical method to standardise and optimise the Philips DoseRight 2.0 CT automatic exposure control system. *J. Radiol. Prot.* 35, 495–506.
- Worrall, M., Vinnicombe, S., Sutton, D., 2020. Determining patient abdomen thickness from a single digital radiograph with a computational model: clinical results from a proof of concept study. *Br. J. Radiol.* 93, 20200010.
- Woussen, S., Lopez-Rendon, X., Vanbeckevoort, D., Bosmans, H., Oyen, R., Zanca, F., 2016. Clinical indications and radiation doses to the conceptus associated with CT imaging in pregnancy: a retrospective study. *Eur. Radiol.* 26, 979–985.
- Yeoman, L.J., Howarth, L., Britten, A., et al., 1992. Gantry angulation in brain CT: dosage implications, effect on posterior fossa artifacts, and current international practice. *Radiology* 184, 113–116.
- Zhang, D., Ayala, R., 2014. Auto Couch Height Positioning Compensation – Making SURE Exposure a Smarter Dose Reduction Tool. Toshiba America Medical Systems CTWP12271US. Toshiba Corporation, Tokyo, pp. 1–8. Available at: www.toshiba-medical.eu/de/wp-content/uploads/sites/2/2015/01/Auto-Couch-Height-Positioning-2014-aquilion.pdf (last accessed July 2016).
- Zhang, X., Chen, J., Yu, N., et al., 2019. Improving image quality with model-based iterative reconstruction at quarter of nominal dose in upper abdominal CT. *Br. J. Radiol.* 92, 20180137.

ANNEX A. DOSE QUANTITIES AND UNITS

(A1)Table A.1 lists specific dose quantities and units used to describe radiation exposure in different x-ray imaging applications. These are not patient doses that relate directly to risks to individuals, but are indicators in terms of air kerma characterising radiation exposure for the purposes of QC, comparison of practice, and setting DRLs as a tool for optimisation. The notation recommended in International Commission on Radiation Units and Measurements (ICRU) Report 74 (ICRU, 2005) on patient dosimetry is given based on the fundamental dose quantities defined in ICRU Report 85a, Revised (ICRU, 2011). Abbreviations in common use and other terms sometimes used for the same quantities are also included.

Table A.1. Dose quantities and units currently used in diagnostic radiology, their recommended notation, and other commonly used symbols, together with the field of application.

Dose quantity	Equation notation (ICRU)	Unit	Abbreviation and other symbols used	Similar quantities	Field of application
Incident air kerma at patient entrance surface	$K_{a,i}$	mGy	K_i ; IAK		Radiography, fluoroscopy
Entrance surface air kerma	$K_{a,e}$	mGy	K_e ; ESAK	Entrance-surface dose*	Radiography and fluoroscopy
Air kerma-area product	P_{KA}	$\text{mGy}\cdot\text{cm}^2$ radiography $\text{Gy}\cdot\text{cm}^2$ (fluoroscopy)	KAP	Dose-area product*	Radiography, fluoroscopy, cone beam computed tomography
Reference air kerma at patient entrance reference point [†]	$K_{a,r}$	Gy	CAK (cumulative air kerma)		Fluoroscopy and fluoroscopically guided interventions
Computed tomography air kerma index	C_K	mGy	CTDI, C_K	Computed tomography dose index*	Computed tomography
Volume computed tomography air kerma index	C_{vol}	mGy	CTDI _{vol} , C_{vol}	Volume computed tomography dose index	Multi-detector computed tomography
Air kerma-length product	P_{KL}	$\text{mGy}\cdot\text{cm}$	DLP, $P_{KL,CT}$	Dose-length product*	Computed tomography
Mean glandular dose [†]	D_G	mGy	MGD, AGD		Mammography

ICRU, International Commission on Radiation Units and Measurements.

*Air kerma and dose in air are essentially equal in diagnostic radiology energy range.

[†]This quantity is a cumulative dose for a procedure. It is not measured directly, but due to the standardised approach for its calculation, it is commonly displayed on x-ray equipment.

A.1. References

- ICRU, 2005. Patient Dosimetry for X-rays Used in Medical Imaging. ICRU Report 74. International Commission on Radiation Units and Measurements, Bethesda, MD.
- ICRU, 2011. Fundamental Quantities and Units for Ionizing Radiation. ICRU Report 85a, Revised. International Commission on Radiation Units and Measurements, Bethesda, MD.

ANNEX B. AUTOMATED SYSTEMS FOR RADIATION EXPOSURE MONITORING

(B1) As discussed in ICRP (2024), larger scale audits of patient doses can potentially be carried out if dose data can be downloaded from electronic storage in DICOM headers or PACS/RIS archives. Dose management systems can be particularly useful for this (Loose et al., 2021; IAEA, 2023). A brief explanation of some of the systems and standards used is given here.

B.1. Digital Imaging and Communication in Medicine

(B2) DICOM is an international standard for storing and exchanging medical images and image-related information (Boos et al., 2016). The DICOM standard is used in the vast majority of digital imaging modalities in medicine and is not a file format; rather, it is a protocol that is used to capture, transfer, store, and display medical data (Pianykh, 2013). Each basic DICOM component is called an ‘object’ and contains the relevant data elements or attributes. There are both image and non-image objects; one example of a non-image object is an RDSR, but there are many other derived structured documents. Each item of equipment that uses the DICOM standard has an associated conformance statement; this details the extent to which the equipment conforms to the standard, and provides essential information regarding interoperability. A plethora of information concerning the DICOM standard can be found at NEMA (2020).

B.2. Radiation dose structured report

(B3) An RDSR is a DICOM information object that records data from radiation events in fluoroscopy, CT, mammography, computed radiography, and digital radiography procedures in a standard format. An RDSR object is like an image, with the major difference that it does not contain pixel data; instead, it contains structured information organised in a hierarchical tree structure (Omar et al., 2016; AAPM, 2019). Without such an object, it would be necessary to use entire image sets to access and store exposure information, with concomitant increases in storage space and transmission requirements. There would also be some loss of data resulting from technical issues (Sechopoulos et al., 2015).

(B4) A vast amount of information is stored in the RDSR structure, including data that are general for all irradiation events, such as device serial number, radiological medical practitioner responsible, and data that are specific for each irradiation event, such as tube voltage and beam angle (Sechopoulos et al., 2015; Hellström, 2018). Modality-specific parameters, such as KAP, DLP, EI, mean glandular dose, and average glandular dose (Annex A), are also recorded as required. The RDSR data are available on most CT scanners manufactured after 2012

(NEMA, 2013), and are available on the newest digital radiography and interventional systems. RDSR support on equipment used for interventional radiology was mandated by IEC in 2010 (IEC, 2022), and should be available on all equipment manufactured subsequently. For example, an entire interventional fluoroscopic sequence involving one pedal press will be included in the RDSR as a single irradiation event (Sechopoulos et al., 2015). So, if a particular interventional examination requires the exposure pedal to be pressed 15 times, 15 individual irradiation events are captured.

(B5) However, there are many attribute fields in the RDSR that are optional rather than mandatory (NEMA, 2016), and each manufacturer has also taken advantage of the possibility to adapt the standard with so-called ‘private fields’ (Malchair et al., 2018). There are consequently many differences between the structured reports provided by different vendors, which makes the task of interrogating them even more complex.

(B6) An RDSR reader is necessary to convert the DICOM object data into a form that is generally accessible. Radiation dose management systems typically enable RDSR data to be viewed, manipulated, and exported. It should be noted that although most current PACS solutions support RDSR storage and review, some legacy PACS have limited ability to handle RDSR data objects (AAPM, 2019). There are open-source solutions, for example OpenRem, which also has a simple skin dose assessment package (McDonagh, 2014).

(B7) AAPM (2019) recommend that a medical physicist needs to verify that radiation generating equipment has the capability of generating a correct RDSR as part of the acceptance test, or as part of a software upgrade for RDSR functionality. Understanding of DICOM and RDSR should be a requirement for medical physicists involved in optimisation of all radiology equipment.

B.3. Picture archiving and communication system

(B8) A PACS is a medical imaging technology which provides secure, economical storage for digital medical images, while allowing convenient access and retrieval for multiple users. Images are stored and transferred using the DICOM format and other data stored in standard formats. A PACS has four major components: imaging modalities; a secured network for transmission of the patient images and data; workstations for the review and interpretation of images; and archives for storage and retrieval of images and reports. Medical documentation and images can be stored securely in off-site servers, and accessed safely from sites in different locations via workstations or mobile devices.

B.4. Radiology information system

(B9) A radiology information system is a networked software system for managing medical images and the associated data. It is used for tracking requests for

radiology imaging, charges, and other associated information. It can be used in conjunction with a PACS and for the management of archives of images and associated records. Methods are required for classification and coding of medical procedures for the future development of radiology information systems.

B.5. The RadLex Playbook

(B10) Downloading exposure data for large numbers of patient examinations using automated systems will facilitate provision and analysis of dose information. However, one problem discussed in Section 4 of ICRP (2023) is the lack of a standard nomenclature for imaging procedures. There may be many variations in names for the same examination used by different departments, even within one organisation. The RadLex Playbook has been created in order to start a process to address this problem in the USA. It provides a set of names for classification of examination protocols to enable a standardised approach to coding and identification for entering procedure data into recording systems such as PACSs and radiology information systems, and is being encouraged by the American College of Radiology (RSNA, 2020). More extensive and unified coding is evolving, and the RadLex Playbook and Logical Observation Identifiers Names and Codes (LOINC) radiology codes have now been merged (LOINC, 2022).

(B11) The names and codes are designed to replace or complement old, inherited, often institution-based names to facilitate the tracking of records for imaging procedures to facilitate requesting, reporting, and archiving of electronic medical records. The Playbook describes imaging examinations as radiology ‘orderables’ that a referring medical practitioner can enter into the system. The orderables may be more general than the specific protocol required to answer the specific clinical question. For example, a ‘CT abdomen/pelvis with contrast’ may be ordered, and a ‘CT abdomen/pelvis with contrast, liver protocol’ examination performed.

(B12) The RadLex Playbook aims to aid the development of a standardised system for coding to facilitate radiation dose comparisons between institutions. Therefore, organisations that use it are expected to map their protocol names to the Playbook. This represents a first stage in the implementation of new procedure names that will need collaboration between clinical staff in different institutions that are aware of local needs and practices, and staff of the vendors who know the system capabilities. There is a long way to go before standardisation is achieved, and progress will be reliant upon the mapping being performed conscientiously and consistently by staff across all institutions.

B.6. References

- AAPM, 2019. Estimating Patient Organ Dose with Computed Tomography: a Review of Present Methodology and Required DICOM Information. AAPM Report No. 246. American Association of Physicists in Medicine, New York.
- Boos, J., Meineke, A., Rubbert, C., et al., 2016. Cloud-based CT dose monitoring using the DICOM-structured report: fully automated analysis in regard to national diagnostic reference levels. *Rofo*. 188, 288–294.
- Hellström, M., 2018. Estimating patient peak skin dose with fluoroscopic procedures. *Phys. Med.* 52, 105.
- IAEA, 2023. Patient Radiation Exposure Monitoring in Medical Imaging. Safety Report Series No. 112. International Atomic Energy Agency, Vienna. Available at: <https://www.iaea.org/publications/14971/patient-radiation-exposure-monitoring-in-medical-imaging> (last accessed August 2023).
- ICRP, 2023. Optimisation of Radiological Protection in Digital Radiology Techniques for Medical Imaging. ICRP Publication 154. *Ann. ICRP* 52(3)
- IEC, 2022. Medical Electrical Equipment – part 2-43: Particular Requirements for the Safety of X-Ray Equipment for Interventional Procedures. IEC 60601-2-43:2022 Edition 3.0. International Electrotechnical Commission, Geneva.
- LOINC, 2022. LOINC/RSNA Radiology Playbook User Guide. Regenstrief Institute, Indianapolis, IN. Available at: <https://loinc.org/kb/users-guide/loinc-rsna-radiology-playbook-user-guide/> (last accessed August 2022).
- Loose, R.W., Vañó, E., Mildenerger, P., Tsapaki, V., Caramella, D., Sjöberg, J., et al., 2021. Radiation dose management systems – requirements and recommendations for users from the ESR EuroSafe Imaging initiative. *Eur. Radiol.* 31, 2106–2114.
- Malchair, F., Dabin, J., Deleu, M., Maccia, C., Merce, M.S., 2018. D 9.141 – Standards for Digital Dose Reporting. VERIDIC Project. European Joint Programme for the Integration of Radiation Protection Research, Brussels.
- McDonagh, E., 2014. OpenRem. Free and Open Source Radiation Exposure Monitoring for the Physicist. The Royal Marsden NHS Foundation Trust, London.
- NEMA, 2013. Standard Attributes on CT Equipment Related to Dose Optimization and Management. XR 29-2013. National Electrical Manufacturers Association, Washington, DC.
- NEMA, 2016. Standard Attributes on X-ray Equipment for Interventional Procedures. XR 31-2016. National Electrical Manufacturers Association, Washington, DC.
- NEMA, 2020. The DICOM Standard. National Electrical Manufacturers Association, Washington, DC.
- Omar, A., Bujila, R., Fransson, A., et al., 2016. A framework for organ dose estimation in x-ray angiography and interventional radiology based on dose-related data in DICOM structured reports. *Phys. Med. Biol.* 61, 3063–3083.
- Piankyh, O., 2013. Digital Imaging and Communications in Medicine (DICOM) – a Practical Introduction and Survival Guide. Springer, Berlin.
- RSNA, 2020. RadLex Radiology Lexicon. Radiological Society of North America, Oakbrook, IL. Available at: <https://www.rsna.org/en/practice-tools/data-tools-and-standards/radlex-radiology-lexicon> (last accessed August 2022).
- Sechopoulos, I., Trianni, A., Peck, D., 2015. The DICOM radiation dose structured report: what it is and what it is not. *J. Am. Coll. Radiol.* 12, 712–713.

ABBREVIATIONS

AAPM	American Association of Physicists in Medicine
ABC	Automatic brightness control (see ADRC)
ADRC	Automatic dose rate control (also known as ABC for image intensifier systems)
AEC	Automatic exposure control
AI	Artificial intelligence
ALARA	As low as reasonably achievable
AP	Antero-posterior
ATCM	Automatic tube current modulation
ATVS	Automatic tube voltage selection
BMD	Bone mineral density
CAK	Cumulative air kerma at patient entrance reference point
CoDE	Conceptus Dose Estimation
CNR	Contrast-to-noise ratio
CSH	Cine series hold
CT	Computed tomography
CTDI	Computed tomography dose index
CTDI _{vol}	Volume averaged CTDI
DAP	Dose-area product (see KAP)
DICOM	Digital Imaging and Communications in Medicine
DL	Deep learning
DLIR	Deep-learning-based image reconstruction
DLP	Dose length product
DRL	Diagnostic reference level
DECT	Dual-energy computed tomography
DXA	Dual x-ray absorptiometry
ECG	Electrocardiogram
EI	Exposure index
EID	Energy integrating detector
EI _T	Target exposure index
ESAK	Entrance surface air kerma. (also $K_{a,e}$)
FBP	Filtered back projection
FGI	Fluoroscopically guided intervention
FP	Flat panel
HU	Hounsfield unit
HVL	Half-value layer
IAK	Incident air kerma [at image receptor or patient entrance surface (also $K_{a,i}$)]
ICRU	International Commission on Radiation Units and Measurement
II	Image intensifier
IR	Iterative reconstruction

KAP	Kerma-area product (also P_{KA}) ICRP Glossary/Air-Kerma, product
LIH	Last image hold
LOINC	Logical Observation Identifiers Names and Codes
mAs	Milliamp seconds (tube current $\times$ exposure time)
ML	Machine learning
MRI	Magnetic resonance imaging
PA	Postero-anterior
PACS	Picture archiving and communication system
PCCT	Photon-counting computed tomography
PET	Positron emission tomography
PMMA	Polymethyl methacrylate
pps	Pulses per second
PSD	Peak skin dose
QA	Quality assurance
QC	Quality control
RDSR	Radiation dose structured report
SAFRAD	Safety in Radiological Procedures (IAEA)
SID	Source to image receptor distance
SNR	Signal-to-noise ratio
SPECT	Single photon emission computed tomography
SPR	Scan projection radiograph (for computed tomography scanning)
SSDE	Size-specific dose estimate

GLOSSARY

Only terms not yet included in the ICRP Glossary are included here. The ICRP Glossary can be viewed at the website address: http://icrpaedia.org/ICRP_Glossary.

Artificial intelligence (AI)

AI can be characterised as a collection of algorithms performing tasks that give a machine the capability to imitate human intelligence. AI is becoming important in medical imaging, as lesions and organs appearing in medical images are too complex to be described by a simple equation or a hand-crafted model as used in conventional computer aided diagnostics. AI methodology has subdomains – machine learning and deep learning – that are used to create decisions based on analysis of large-scale training data sets.

Automatic dose rate control

Device that automatically determines the exposure rate needed to provide an image of selected image quality during fluoroscopy by sampling the x-ray intensity transmitted through the patient at the image receptor. The changes in exposure are achieved through adjustment of the tube potential (kV) and tube current (mA) according to pre-determined relationships.

Automatic tube current modulation (ATCM)

ATCM or automatic exposure control determines the tube current level in computed tomography required to maintain the level of image quality or image noise selected by the operator throughout a scan. The adjustments are based on the scan projection radiograph recorded before the main scan.

Conceptus

The term ‘conceptus’ is used to describe all prenatal tissues from the moment of conception until birth, thus including both the embryo and fetus.

Contrast-to-noise ratio (CNR)

CNR is the contrast divided by the noise. Contrast means the difference between pixel values of any two regions in the image. Noise means the graininess of the image which is typically described by a single value representing the standard deviation of pixel values within a (homogeneous) region in the image. Note: This quantity needs to be introduced because attention to the ‘contrast’ alone has often resulted in images of higher quality than needed for confident diagnosis. Noise is also a measure of image quality. Images having higher noise

levels do not necessarily undermine diagnostic accuracy; rather, the CNR may be similar or improved.

Deep learning (DL)

DL is a subset of machine learning developed to learn from data without being programmed explicitly. In DL, the data are fed through several data processing layers in a neural network architecture, providing higher abstraction level features from the original input data. As with machine learning, DL methods require to be trained using datasets containing large numbers of appropriate images, and has become feasible due to the enormous number of medical images now being produced. DL methods are yielding promising results in medical imaging related to diagnostic tasks, such as lesion or tissue localisation, segmentation, classification, and prediction of clinical outcomes. DL image reconstruction is being used for computed tomography.

Digital Imaging and Communications in Medicine (DICOM)

Digital imaging standard describing a set of protocols describing how radiology images are identified in a structured way, formatted, and communicated. DICOM is manufacturer-independent and was developed by the American College of Radiology and the National Electronic Manufacturers Association. Provision of an agreed structured format facilitates the exchange of files between devices that have the capability of accepting image and patient data in DICOM format. DICOM 3.0 is the current version. Available at: <http://medical.nema.org/>.

Dose management system

A dose management system comprises software that can store information on patient dose quantities that is designed to aid the imaging team in optimisation of radiological protection. Tasks performed by such a system might include collecting dosimetric data to establish local diagnostic reference levels, checking compliance with diagnostic reference levels, and provision of data at the time imaging is being performed to aid optimisation, especially for computed tomography and interventional procedures. Dose management systems can also assist in the prevention, detection, and reporting of unintended exposures. Other terms such as ‘radiation exposure monitoring’ and ‘radiation dose monitoring’ are used to describe dose management systems.

Entrance surface air kerma (ESAK, $K_{a,e}$), see Air kerma, entrance surface in ICRP Glossary

Flat panel detector

Image sensor used in solid state digital radiography devices containing an array of semi-conductor elements similar in principle to the image sensors used in digital photography. They are used in both projection radiography and as an alternative to x-ray image intensifiers in fluoroscopy equipment.

Iterative reconstruction

Computed tomography image reconstruction technique which typically applies repeated iterative loops of forward projection (producing simulated projection raw data) and back projection (creating image from projections). Thus, the image reconstruction happens by several iteration cycles where the iterated image gradually approaches the final image result converging either by computed tomography image pixel values or by the difference between the simulated and true (measured) raw-data projections. Iterative methods may apply different levels of physical modelling of the computed tomography scan, where increased modelling may enable higher image quality while also adding to the computational complexity and calculation time.

Kerma-area product (KAP, P_{KA}), see Air-kerma, product in ICRP Glossary

Machine learning (ML)

ML involves the development of computer programmes that can find complex patterns, which might represent lesions or other features, within complex data sets. ML has been developed to learn from data without being programmed explicitly. In medical imaging, a model or mathematical algorithm is trained on image data sets to enable it to predict an outcome for new patient data similar to that given by a human expert. ML predicts outcomes from new data based on earlier training on large scale. See also Deep learning.

Medical physicist

A health professional with specialist education and training in the concepts and techniques of applying physics in medicine and competent to practise independently in one or more of the subfields (specialties) of medical physics. In this publication, the specialty concerned is diagnostic radiology, but, alternatively, medical physicists may specialise in radiation therapy or nuclear medicine. Competence of persons is normally assessed by the state through a formal mechanism for registration, accreditation, or certification of medical physicists in the various specialties. Medical physicists who have attained the required level of competence and become registered may be referred to as medical physics experts, qualified medical physicists, or similar. States that

have yet to develop such a mechanism would need to assess the education, training, and competence of any individual proposed by the licensee to act as a medical physicist, and to decide, on the basis of either international accreditation standards or standards of a state where such an accreditation system exists, whether such an individual could undertake the functions of a medical physicist, within the required specialty.

Noise

Noise means the graininess of the image which is typically described by a single value representing the standard deviation of pixel values within a (homogeneous) region in the image. Noise can also be described by a noise power spectrum which describes the spatial frequency distribution of the noise. This can also be described as the grain size distribution of the image noise, or noise texture. Therefore, noise power spectrum is a more comprehensive description of the noise compared with single value noise determined from pixel standard deviation.

Patient radiation exposure monitoring

Components, mechanisms, and operational processes related to recording, collecting, and analysing patient radiation exposure data associated with clinical imaging operation. Here, monitoring refers to capturing and meaningfully evaluating patient radiation exposure data, and not the actions for quality improvement, an ultimate goal undertaken by managing patient radiation exposure data.

Radiological medical practitioner

A health professional with specialist education and training in the medical uses of radiation, who is competent to perform independently or to oversee radiological procedures in a given specialty. This includes cardiologists, orthopaedic surgeons, and other clinicians who have undertaken appropriate training for this role. Competence of the person is normally assessed by the state through a formal mechanism for registration, accreditation, or certification of radiological medical practitioners in the given specialty.

Radiation dose structured report

Part of the DICOM standard defining the set of DICOM objects providing the radiation-dose-related parameters by hierarchical description of the irradiation event (e.g. within entire computed tomography examination or pulsed fluoroscopy image series).

Radiology information system

A system that supports the information processing and business requirements of radiology departments and freestanding image centres.

Reference air kerma ($K_{a,r}$)

The air kerma at a point in space located at a fixed distance from the focal spot (see ‘Patient entrance reference point’ in ICRPædia Glossary) accumulated from a whole x-ray procedure expressed in Gy. The International Electrotechnical Commission (IEC, 2022a) refers to this quantity as ‘reference air kerma’, while the US Food and Drug Administration uses the term ‘cumulative air kerma’ (CAK). The International Commission on Radiation Units and Measurements has not defined a symbol for this quantity. $K_{a,r}$ is the notation introduced by the National Council on Radiation Protection and Measurements (NCRP) in Report No. 168 (NCRP, 2010). In many medical publications, the acronym used for this quantity is CAK. This quantity is referred to in older medical publications as ‘cumulative dose’ and has also been called ‘air kerma at the patient entrance reference point’ and ‘reference point air kerma’.

Scan projection radiograph (SPR)

Radiographic image produced on a computed tomography scanner by moving the couch through the computed tomography gantry with the x-ray tube in a fixed position. Scan projection radiographs are performed at the start of a computed tomography examination, and are used for selecting the region of the body to be scanned and providing a measure of attenuation along the body for adjustment of tube current in automatic tube current modulation. A variety of terms are used for the SPR by different vendors: namely scout view, topogram, survview, and scanogram.

Signal-to-noise ratio (SNR)

SNR or S/N is a measure that compares the level of a desired signal to the level of background noise. Closely related to CNR but instead of contrast, as in CNR, the signal is involved in SNR.

Spatial frequency

Any signal can be composed of a series of harmonic (sine and cosine) waves. An image can be interpreted as a composition of an infinite number of periodic sine and cosine waves. A short wavelength (equivalent to high spatial frequency) corresponds with small detail, whereas a long wavelength (equivalent to

low spatial frequency) corresponds with large objects in the image. The relationship between spatial frequency and detail size is inversely proportional. In order to avoid confusion with the term time frequency, spatial frequency is used. A common unit is line pairs per millimetre (lp mm^{-1}).

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* Although formally not a Main Commission member since 1988, the Scientific Secretary is an integral part of the Main Commission.

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