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

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

ICRP PUBLICATION 15X

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Abstract Digital radiology is playing an increasingly important role in medicine world-wide. The use of computed tomography (CT) has risen dramatically in recent decades and makes up about 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 15x* (ICRP, 2022), three fundamental requirements for taking the optimisation process forward were described. These are 1) the need for collaboration between radiologists and other physicians, radiographers, medical physicists and managers, 2) access to the appropriate methodology, technology and expertise, and 3) provision of organisational processes that ensure tasks, such as equipment performance tests, patient dose surveys and reviews of protocols are carried out. A high-level requirement is the integration and use of decision sciences, and harmonisation of these optimisation processes across multispecialty 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 others there is little or no medical physics support. This presents challenges in communicating requirements for optimisation. This document addresses these challenges by providing information for facilities, within broad categories linked to optimisation arrangements already in place, D: Preliminary, C: Basic, B: Intermediate, and A: Advanced (ICRP, 2022). 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.

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, radiographers and medical physicists and developed from the initial level D when a facility is set up, to the basic requirements of optimisation level C, through the intermediate level B, to advanced processes of optimisation level A, as set out in this report.**
- **Exposure factors for digital radiography should be established for different anatomical regions and patient characteristics, making use of automatic exposure control devices and possible use of copper filtration, especially for paediatric exposures, and 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 monitored through regular quality control.**
- **Development of protocols for CT 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 lower dose settings to be used.**
- **Paediatric protocol optimisation requires an understanding of clinical indications, patient sizes, and the ability of patients to cooperate and, as for all 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 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 correct 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 there are many aspects that need to be in place before an x-ray facility can even embark on the road to achieving optimisation; these are not straight forward and have become quite complex in the healthcare environment. Proper initial education and ongoing training of staff on 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 gradually improve overall effectiveness (ICRP, 2022). Optimisation of medical imaging involves continuing improvement with the development of knowledge, skills, competencies, and experience.

(3) *Publication 15x* sets out three building blocks on which strategies for achieving optimisation should be built (ICRP, 2022). The cornerstone is professionalism; namely collaboration between professionals, with radiologists, radiographers and medical physicists working together as a team within an organisation that provides a structure to facilitate the process. The radiologist can judge whether the image quality is sufficient for the diagnostic purpose, 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. The clinician, radiologist, 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. The requirement to put in place processes to manage the activities that ensure a quality assurance 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.

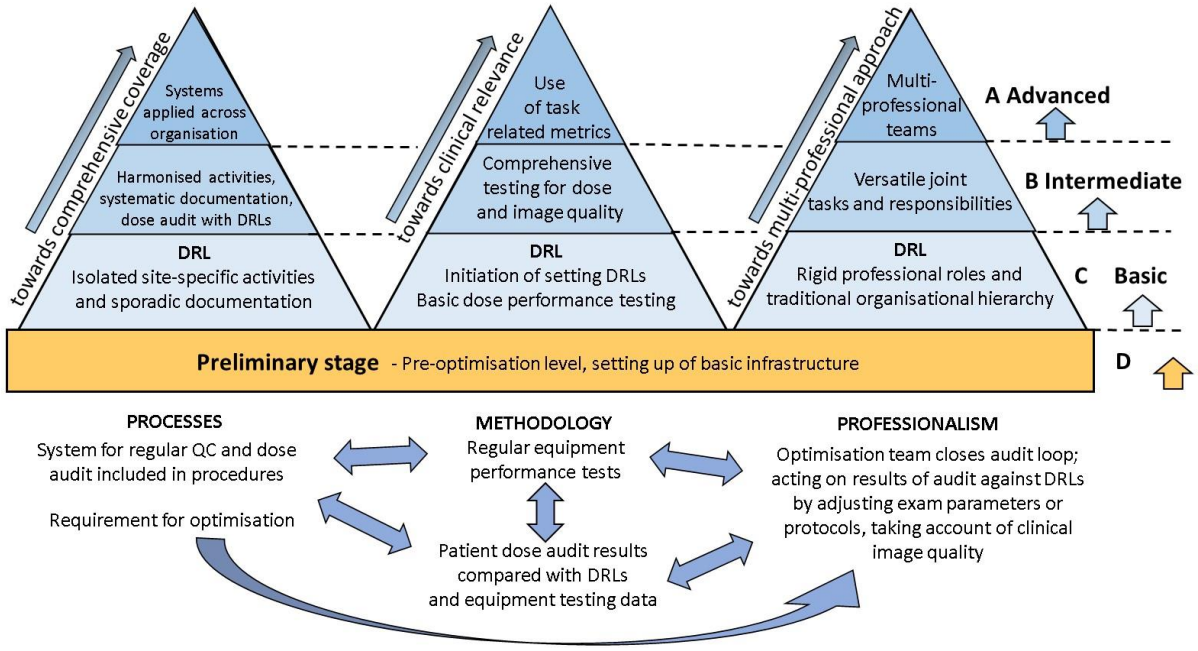


Fig.1.1. The three main components in the development and maturation of optimisation; processes, methodology and professionalism. The levels represent different stages in achievement moving upwards from D, through B, and C, towards A. Level D represents a basic infrastructural level as a prerequisite for initiation of the optimisation process. A, B, and C set out the arrangements that will be in place for each component when that level is achieved. The lower section shows the stage after the adoption of DRLs (whether local, national or regional) has occurred. Processes are in place to require both regular quality control (QC) tests and dose audit against the DRLs, and use of the information obtained in optimising protocols and providing feedback, indicated by the arrows.

(6) There are large variations in the levels of knowledge, skills and competencies (KSCs), 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 others 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, since facilities will be at different stages in the process and have different arrangements in place. Therefore, priorities for appropriate action will depend on what should be the next stage in their development.

(7) This document attempts to address those challenges by providing detail for facilities, within broad categories for levels of optimisation, divided into D: Preliminary (before actions have been taken to start the process of optimisation); C: Basic; B: Intermediate; and A: Advanced, as described in *Publication 15x* (Fig. 1.1). Advice and training from experts through

the International Atomic Energy Agency 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 15x* attempts 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 KSCs 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). In radiation therapy, the dose to normal tissue should be kept as low as possible, within the conditions required to achieve the therapeutic objective. 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 be provided to end users. This training typically is provided by the vendor application specialist but the medical physicist and radiographer supervisors 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 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 15x* that contains sections dealing in more depth with considerations of equipment installation and life cycle, dose audit and image quality

analysis (ICRP, 2022), 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 chapter 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) The publication is aimed at radiologists, interventional proceduralists, 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 radiologists and radiographers. There are also approaches for interventional procedures in Section 3, which will be of prime interest to radiologists and other clinicians performing them, but 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 AI 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, 2022). However, there are many technical, legal and ethical challenges to be solved before it 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 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 explicitly programmed. 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 et al., 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.

(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 a ML/DL approach and ultimately replace traditional methods such as model observers for image quality assessment and Monte Carlo simulations for dosimetry calculations (Samei and Kruipinski, 2018, Inkinen at 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 measures in hospitals to ensure the methods are appropriate for local patient cohorts. 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 focussing on the technical requirements for optimisation with regard to the various modalities using ionising radiology, namely radiography, fluoroscopy, and CT. These documents have provided practical methodologies for optimisation to address the needs arising from the development of new technologies.

(18) Digital radiography enabled the image data to be processed to give images optimised for viewing, but made high (and low) exposures more difficult to identify. ICRP prepared a report to facilitate the transition from film/screen to digital radiography (ICRP, 2004). Section 2 of this report will extend the advice given and deal with the pitfalls in optimisation during routine use of digital radiography.

(19) In the meantime, the rapid development of fluoroscopically guided interventions had led to the appearance of cases of tissue reactions in patients in radiological imaging. A report on guidance to avoid radiation injuries was published to address this risk (ICRP, 2000b). Other publications have since followed to provide 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 will augment the measures described for general optimisation of patients' exposures in these reports, but will not deal with the risk of tissue reactions to the same depth. ICRP recently provided a detailed report on occupational radiological protection for interventional procedures (ICRP, 2018a) so this report will not deal with occupational exposure issues in any depth, but emphasises that occupational protection should be managed in an integrated approach with patient protection.

(20) ICRP has two publications that cover optimisation in terms of managing patient dose in conventional CT, for single slice and multi-slice CT (ICRP, 2000c, 2007a). However, there

has since been a huge development in CT hardware and software such as iterative reconstruction that were not discussed in the earlier publications, and others such as automatic tube current modulation for which the software has evolved since the previous publication. There will be extensive discussion of opportunities for optimisation in CT in Section 4, as well as risks of higher dose levels if potential dose reduction features are not fully understood and/or used incorrectly. In addition, ICRP has published a report on cone beam CT (ICRP, 2015), but discussion in this document is confined to the application of cone beam on C-arm fluoroscopic and interventional units. ICRP Task Group 117 will provide a report on CT optimisation when used with positron emission tomography (PET) and single photon emission tomography (SPECT) in hybrid imaging (ICRP, TG117).

(21) 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 ICRP (2013b). The optimisation methods for paediatric imaging will be developed further in Section 5. 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 considers the approach to optimisation of exposures during pregnancy in terms of minimising the dose to the embryo/fetus and assessing the dose delivered.

(22) The present publication covers the application of digital radiology to medical diagnostic and interventional applications. The content will replace material in *Publication 93* on technical issues in digital radiology, and *Publications 87* and *102* on CT, and will supplement material in *Publications 85*, *117* and *120* linked to specific applications of fluoroscopy and interventional procedures, *Publication 121* on paediatric imaging, and *Publication 135* on DRLs. The document does not include mammography for which detailed specialist texts are available, the application of imaging in radiotherapy treatment, which will be covered in a future publication (ICRP TG116), or dental radiology.

(23) The dosimetric quantities used with the various modalities are listed in Annex A. The tools that accompany digital imaging from Radiology Information Systems (RIS), to Picture Archiving and Communication Systems (PACS), and Dose Management tools facilitate workflow, allowing easier storage and transfer of image data, image manipulation and merging, and recording of exposure details, are described in Annex B.

2. DIGITAL RADIOGRAPHY

(24) **Key messages 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 (DR) 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.**
- **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, and 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. "Virtual grid" software can be useful where there are practical difficulties in mobile radiography, but will not replace the physical grid.**
- **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.**
- **AEC devices should be calibrated to suit the characteristics of the detector and can be set up to maintain a constant Exposure Index. 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 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 gonadal shielding during x-ray based diagnostic imaging should be discontinued as routine practice.**
- **Data on rejected images should be collected and analysed regularly. Reject rates should be calculated and quality improvement actions taken when they rise above a predetermined threshold. Reasons for rejects should be used to steer improvements in working methods.**
- **Acceptance testing and commissioning are crucial to ensure new equipment is performing optimally. After commissioning, medical physicists and radiographers should work together to establish a local QC/QA programme. Radiographers, radiologists, and medical physicists should collaborate to identify the most appropriate processing algorithms for reporting radiographs.**

2.1. The digital radiography system

(25) Radiography is the fundamental radiological imaging process and is in widespread use

throughout the world in different types of facility. 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.

(26) 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 of 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 15x* (ICRP, 2022).

(27) 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.

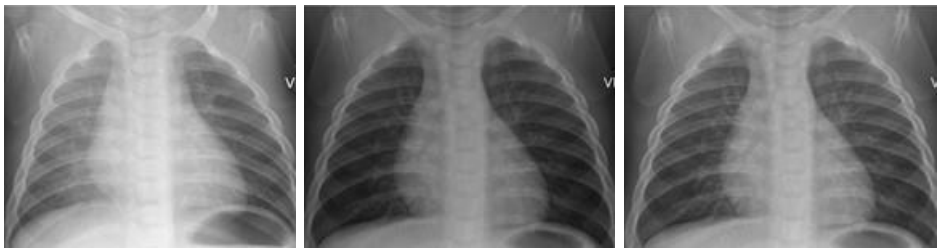


Fig. 2.1. Presentations of the same chest image using different post processing look up tables-using an underexposed appearance at left, overexposed in middle, and optimised image at right (Dean Pekarovic, University Medical Centre Ljubljana, Slovenia).

(28) 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 (CR), as this can be used with existing x-ray equipment, the film/screen cassette simply being exchanged for a CR one. However, the x-ray unit automatic exposure control (AEC) system should be recalibrated to suit the characteristics of the CR or direct digital radiography (DR) detector – a point that is often overlooked (ICRP, 2004; Doyle and Martin, 2006; IAEA, 2015). Full DR systems offer more detailed preinstalled protocols including not only tube kV and mAs selection, but source image-receptor distance (SID), additional filtration, field of view (FOV), position of image receptor, use of radiographic grid, and post processing tools.

(29) 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 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 radiologists, enables complaints about poor image quality and comments on what can be improved in radiographic technique to be fed back and changes implemented. This link is crucial, especially in relation to specific clinical indication examination protocols (Image Wisely, 2022a, case 4).

(30) CR and DR images are reviewed by radiologists on diagnostic quality displays (DICOM calibrated), but the display on the radiographers' 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 by radiographers are of a poorer quality, it will

be more difficult for them 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, and adaptable room illumination conditions with the capability for dimming.

Box 2.1. Digital radiography technology

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

Digital radiography (DR): The image recorded is stored directly in a diode array within the imaging detector. The image receptors contain phosphors or photodiodes that convert x-ray energy into light or an electrical signal that can be recorded (ICRP, 2004; EC, 2004; IPEM, 2010). The types of system can be subdivided into:

- *Indirect X-ray capture digital radiography (IDR):* IDR systems contain a phosphor plate backed by a diode array. Caesium iodide (CsI) imaging plates used in many DR systems have thicker phosphor layers with needle shaped crystals and are substantially more sensitive than systems using gadolinium oxysulphide (Gd_2O_2S) or other phosphors (ACR-AAPM-SIIM-SPR, 2017).
- *Direct x-ray capture digital radiography (DDR):* DDR systems comprise a conductive layer of a semi-conductor, such as selenium or cadmium telluride, backed by an array of electrodes. X-ray photons are converted into electron-hole pairs in the semi-conductor (Queiroz et al., 2020).

(31) The measurable quantities used to monitor patient dose in radiography are incident air kerma at patient entrance surface (IAK, K_i), the entrance surface air kerma (ESAK, $K_{a,e}$), which may be calculated from exposure factors or measured with dosemeters, and the kerma-area product (KAP, P_{KA}) measured by a meter attached to the output port of the x-ray unit. These are listed in Annex A and more information on their use is given in ICRP (2017, 2022).

(32) Since the greyscale level is optimised in digital radiography, the primary feedback on exposure, unless a KAP meter is fitted, will be through the exposure index (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 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). EI values 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 CR cassettes with time will be apparent through change in the EI.

(33) 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 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

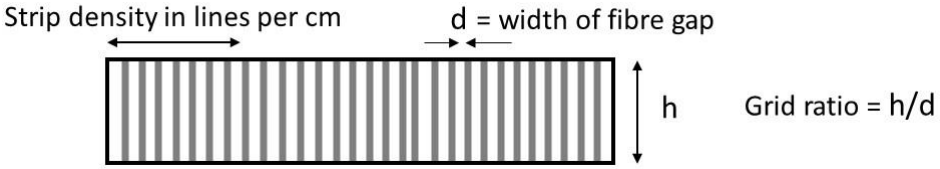
(34) X-ray beams used for medical imaging contain photons with a wide range of energies

determined by the x-ray tube potential and filtration. Lower energy x-ray photons provide good 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. 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, 2022). 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.

(35) The choice of tube potential is a crucial component of optimisation in radiology. Tube potentials of 70 kV to 90 kV will generally be used for exposures of the trunk, with values being increased for larger patients; 50 kV or 60 kV will be used for extremities; and 55 kV to 70 kV for premature infant, neonatal, and infant chest/abdomen radiography. However, the tube potential values are higher (kV 120–140) when a grid is used for chest images on fixed radiographic units (anti-scatter grid of at least 10:1, preferably 12:1) (ACR-SPR-SIIM-STR, 2017) (Box 2.2).

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 inter-space 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. Grid ratio depends on the modality and the source to imaging distance (SID). 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 focussed 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.

(36) 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, together with other information about the exposures, are given in

Table 2.1. The values in the table are approximate and 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). The exposure parameters 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 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 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.

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

Anatomy	Projection	kV	Grid	Additional filtration (mm Cu)	ESAK* (mGy)	KAP* (Gy cm^2)
Chest	PA	120–140	Yes		0.05–0.2	0.06–0.1
Chest	PA	75–85	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
New-born <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 m–3 y)	AP/PA	60–80	No	0.1–0.2	0.04–0.08	0.005–0.022
Infant 5–15 kg abdomen pelvis (4 m–3 y)	AP	60–80	No	0.1–0.2	0.3–0.6	0.05–0.15
Child 15-30 kg chest (4 y–10 y)	AP/PA	70–85	No	0.1–0.2	0.06–0.12	0.008–0.05
Child 15–30 kg abdomen pelvis (4 y–10 y)	AP	70–80	Yes	0.1–0.2	0.5–1.5	0.15–0.25

*Dose quantities represent a range of average values (1st and 3rd quartile values in a dose survey) and the adult ones are for a 70 kg patient. If an indirect DR system with CsI is used, then values should be towards the lower end of the range or lower. PA – postero-anterior, AP - antero-posterior. Doses from improved modern systems may go below the values listed.

(37) 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 about 12 cm or low attenuation exams 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 DR systems may also incorporate virtual grid algorithms where the effect of scatter is corrected computationally in the acquired images (see Section 2.3.3).

(38) Grid cassettes are used with mobile units in which the grids are lighter and easier to handle. Since 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.

(39) 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 whether the grid is in place.

(40) In order to achieve a consistent exposure level, an automatic exposure control (AEC) device is usually employed in fixed radiographic imaging facilities that terminate exposures at predetermined 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.

(41) 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 roughly as kV^2. 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)

(42) 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 aluminium equivalent total filtration is the minimum requirement in the UK.

(43) 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 CsI DR systems. However, adding excessive copper filtration can result in reduction of image contrast with less differential between grey tones.

2.2.2. Automatic exposure control (AEC)

(44) AEC devices are employed to control exposures and improve the consistency of image acquisition. An AEC 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 among 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 AECs is recommended whenever possible although small children may require manual techniques.

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 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 DR 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 CsI DR 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 AEC 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.

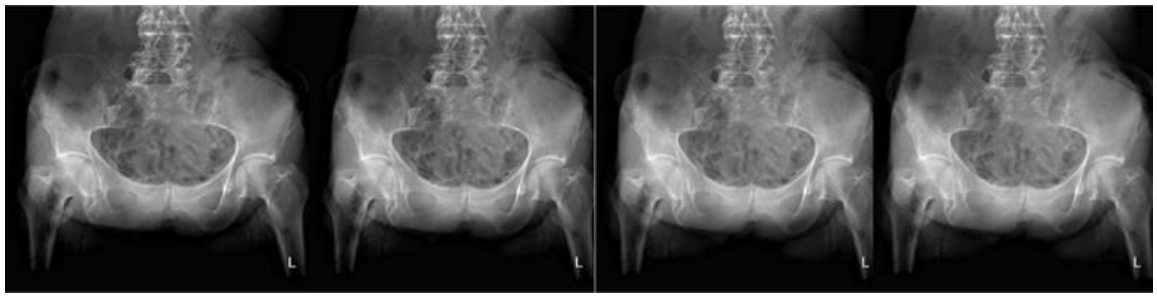


Fig. Pelvic radiographs taken at 81 kV with a Siemens Axiom Aristos FX showing the effect of additional copper filters. Exposures from left to right were taken with the following thicknesses of copper 0 mm, 0.1 mm, 0.2 mm, and 0.3 mm, and KAP values are 34 cGy cm^2, 22 cGy cm^2, 14 cGy cm^2, and 11 cGy cm^2, respectively (cadaver study- Dean Pekarovic, University Medical Centre Ljubljana, Slovenia).

(45) AEC devices should be calibrated to suit the characteristics of the detector and can be set up to maintain a constant Exposure Index (see Section 2.2.3, Fig. 2.2). 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 to ensure consistency.

(46) The variation in sensitivity of a digital detector with photon energy and so tube potential depends on the phosphor material. While the sensitivity of CsI DR systems increase with tube potential, that for CR systems decline, so the relative exposure needs to be increased slightly at higher tube potentials (Doyle and Martin, 2006). The exposure index (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 signal-to-noise ratio (SNR) (Section 2.2.3). Therefore, maintaining a constant EI is recommended as the method of choice for setting up AECs for digital radiography.

(47) The noise level in the image and the SNR are determined by the image receptor sensitivity and the exposure level and the AEC 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 should be set up at installation of a new type of image receptor. AEC devices are usually set up relative to a predetermined air kerma incident on the detector at 80 kV, and use different kV compensation curves, so that the AEC 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 and physicists) is crucial.

(48) Considering quality levels required for different imaging tasks, high might correspond to an air kerma incident on the image receptor of 0.2–0.5 mGy, medium to 0.1–0.25 mGy, and low to 0.05 to 0.12 mGy. The lower end of each air kerma range might correspond to that required for a DR system and the upper end for a CR system. The majority of AEC systems 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.

(49) The AEC chambers selected will depend on the examination and the exposure level required in the region of interest. In modern units the chambers used, together with exposure factors will be preselected 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 patients' thicknesses (IPEM, 2010).

(50) A common mistake in use of an AEC is not centring the anatomical area of interest on the relevant chamber. There may be greater risks for certain examinations, for example in 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

(51) 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 having higher or lower noise levels than is required are not readily recognizable at the time images are taken, so there a risk of dose creep and increases of 40% in dose have been reported (Gibson and Davidson, 2012). Exposure indicators have been developed by manufacturers of digital image detectors and later standardised following the recommendation of AAPM Task Group 116 (AAPM, 2009) and more recently AAPM Task Group 232 (Dave et al., 2018).

(52) 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 exposure index (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. Since 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 deviation index (DI) derived as:

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

(53) 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 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 commission of a new x-ray equipment. During clinical use, the deviation index (DI) should be used by radiographers to identify images that are under or over exposed so that appropriate action can be taken (Table 2.2). A DI of 0 indicates the proper exposure, a DI above +1 a higher exposure than expected and a DI less than −1 is lower. Actions relating to different DI values are listed in Table 2.2 (AAPM, 2009).

Table 2.2. Recommended values of Deviation Index (DI) for determining acceptable imaging settings and required actions (AAPM, 2009)

DI	Action required
> +3	Excessive patient radiation exposure. Repeat only if relevant anatomy is clipped or "burned out". Require immediate quality assurance (QA) management follow-up
+1 – +3	Overexposure. Repeat only if relevant anatomy is clipped or "burned out".
−0.5 – +0.5	Target range
<−1	Underexposure. Consult Radiologist for possible repeat
<−3	Repeat (consider QA programme)

(54) It is important for radiographers and radiologists to understand the usefulness of exposure indicators, how they 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. There have also been vendor specific definitions for EI, so users of older equipment should be aware that factors may be different.

(55) 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 values of DI, facilities can control dose creep. Analysing the percentage of images that fall outside an acceptable range can be used to educate technologists and decrease the variation while improving image quality goals of the department.

(56) It should be noted that the value of EI can be quite dependent on the manufacturer. In addition, the definition has evolved with time and older CR systems from different manufacturers used completely different definitions. The user needs to know how their system

performs and obtain calibration tables for EI versus dose to detector or noise in a simple phantom, if there are uncertainties, or if different manufacturers cohabit in the same facility.

Procedure	Number	KAP_average ($\mu Gy.m^2$)	KAP_median ($\mu Gy.m^2$)	DRL ($\mu Gy.m^2$)	KAP_med/DRL	EI_average
T084 Pelvis AP	238	44.7	39.4	200	0.20	340
T084 Pelvis AP	188	48.1	42.6	200	0.21	322
T026a Lumbar-spine AP	171	43.6	35.4	130	0.27	327
W019a Cervical-spine AP	147	7.04	6.0	30	0.20	269
T090a Hip AP	137	25.5	24.0	95	0.25	312
W019b Cervical-spine Lat	131	6.25	5.7	35	0.16	326
W050 Shoulder joint AP	131	8.7	7.6	30	0.25	387
L026b Lumbar-spine Lat	130	187	155	230	0.68	360
L026b Lumbar-spine Lat	124	163	150	230	0.65	395
T026a Lumbar-spine AP	106	56.1	47.7	130	0.37	321

Fig. 2.2. A spreadsheet chart used for monitoring KAP and EI values for selected radiographic examinations. The exposure index target value (EI_T) was set at 250, but could be modified by the user for each projection. (Urban Zdešar, University Medical Centre Ljubljana, Slovenia, reproduced with permission).

2.3. Other aspects of optimisation

2.3.1. Source to image receptor distance (SID) and focal spot size

(57) 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 about 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.

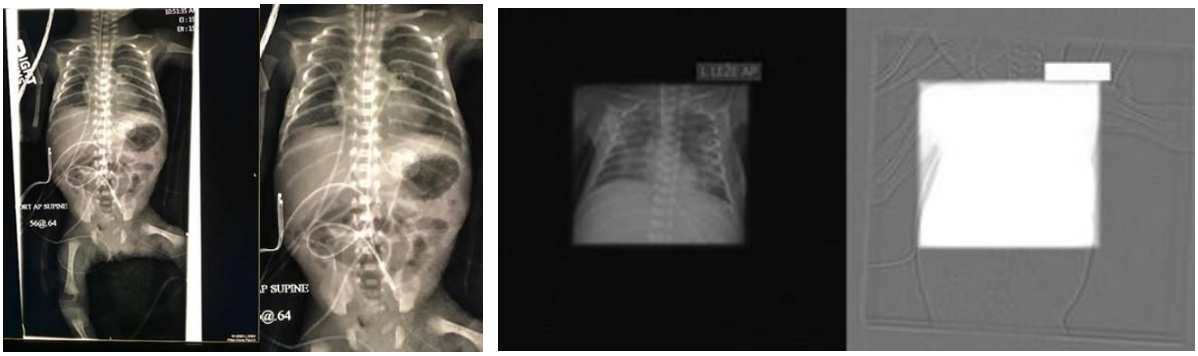
(58) Increasing the SID can be used to reduce image magnification in order to include the complete anatomy within the image for large patients. The inverse square law should be used to achieve the same dose at the image receptor, although if the patient is large then it may be appropriate to increase the tube potential as well. However, the grid focal distance should be taken into account in determining the correct SID.

(59) 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 DR, and if the prolonged exposure time is acceptable regarding patient motion. Some reports suggest that differences between small and large focus are not visible in DR, but experienced radiologists 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 (FOV) and Collimation

(60) Essential to every radiographer's training is the importance of collimating the x-ray

beam to the anatomy to be imaged. This is facilitated for CR by the wide range of cassettes available, which encourages radiographers to consider image size, but DR 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 DR receptor options such as neonatal chest receptors are being offered but they are expensive. Radiographers have a simple tool available to crop DR 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 it will also produce more scatter from the surrounding tissues and so 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 the example in Fig. 2.3a and b.



a b c d

Fig. 2.3. Issues in image collimation. 2.3a and b show a portable babygram in a neo-natal intensive care unit to determine umbilical vein catheter placement position; a) The original image which is poorly collimated, and b) image with the appropriate collimation (Kimberly Applegate, USA). 2.3c and d exemplify very poor practice. They show an ostensibly collimated image which is in fact cropped. C shows the image with a normal window width and level, whilst d shows the image with an adjusted window width and level, demonstrating the actual radiograph as exposed. Images of this type can be used for auditing poor collimation practice where this is an issue (Dean Pekarovic, University Medical Centre Ljubljana, Slovenia).

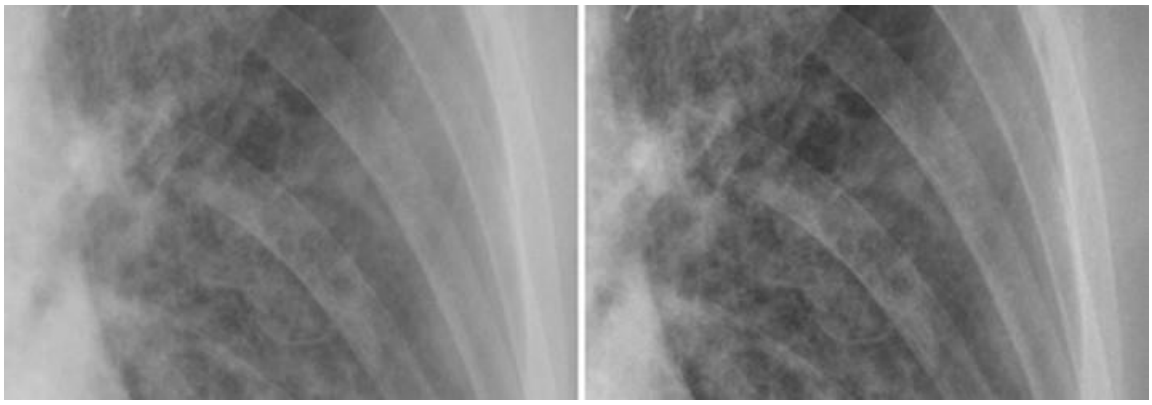
(61) The central importance of collimation for patient dose (and KAP values) and image quality cannot be overemphasised throughout radiographer training. Suboptimal practice should be identified through regular audit of KAPs against expected values. In departments where collimation practice is suboptimal,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

2.3.3. Virtual Grids

(62) Some vendors offer “virtual grid” software, sometimes called “grid less” or “scatter correction” software, which incorporate algorithms to reduce scatter in the acquired images (Mentrup et al., 2014). 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.

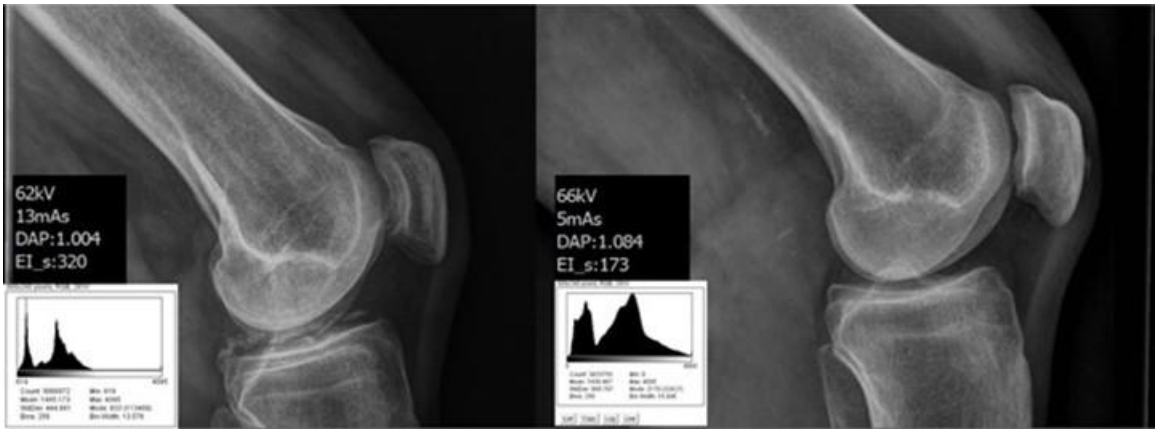
Virtual grids may enable more extensive radiographic imaging without grids and help to maintain sufficient image quality as regards to scatter, e.g. in mobile chest x-ray imaging. Examples of chest images before and after application of a virtual grid are shown in Fig. 2.4 and images obtained with a standard and a virtual grid are compared in Fig. 2.5.

(63) 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, then a check must be carried out afterwards to ensure that it is replaced and in the correct orientation before a new patient is imaged.



a b

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



a b

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 (Dean Pekarovic, University Medical Centre Ljubljana, Slovenia).

2.3.4. Patient protective equipment (shielding devices)

(64) 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 DR examination have declined, and shielding can negatively affect the efficacy of the examination (AAPM, 2019c). 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 generally recommended, and the effectiveness of shielding outside the FOV is minimal. However, consideration should be given to protection of the breast, gonads and thyroid where these organs lie within 5 cm of the primary beam (ICRP, 1982, 2013b) (Table 2.3). 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.

Table 2.3. 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 then 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 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 less than 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 eye lens	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.

(65) Patients or carers may be more comfortable if gonadal shielding is used, as it has been a rule of good practice for many decades, but this is not a reason for resisting the change in practice. Changing the practice will take time, requiring stakeholder education and raising awareness of professionals such as clinicians and radiographers, as well as of carers, patients and families.

(66) During training, radiographers must be aware that not only gonadal shielding but 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. This includes limbs, which if incorrectly positioned may overlie important anatomy (Image Wisely, 2022). For chest x-rays with lateral projections and elderly patients requiring 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.

2.3.5. Reject analysis

(67) A reject and retake analysis programme should be in place to allow radiographers to learn when images are suboptimal or non-diagnostic. 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 images in digital radiography is complex and time consuming (Jones et al., 2015; AAPM, 2015). There may no longer be physical evidence of rejected images and on early systems radiographers simply deleted unwanted images with no record being made. This is 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.

(68) Reject and retake analysis should be included as part of the QA programme and enacted through the quality management system (ICRP, 2022). Data should be collected regularly and analysed on a monthly basis. Reject rates should be calculated and documented by body part and facility location, and education/training or corrective action taken if rejected image rates are above a predetermined threshold or start to rise. Rejects should be reviewed as a collaborative task with radiologists and radiographers, and reasons highlighted as this can be a powerful self-assessment tool to enable and encourage improvement in practice.

2.4. Factors to consider in optimisation

(69) The various factors, termed actions, that can influence digital radiography dose and quality, many of which have already been mentioned, are brought together in Table 2.4. These actions which can increase or decrease patient dose, are based on Table 2.3 in ICRP (2004) but extended to include a wider range of actions.

Table 2.4. Actions that can affect patient dose and image quality

Action	Effect on dose	Influence on image quality or diagnostic information
Increase mAs to reduce noise perception	Increase	Improvement in SNR
Increase mAs further to give 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

Table 2.4. *(continued)*

Action	Effect on dose	Influence on image quality or diagnostic information
Reduction in number of images per procedure (e.g., avoiding the lumbosacral spine image)	Decrease	Remains unchanged
Increase source to detector distance	Decrease	Improve geometry
Increase in size of x-ray tube focus	Unchanged	Reduced spatial resolution, decrease in exposure time
Decrease in size of x-ray tube focus	Unchanged	Improved spatial resolution
Expose full DR image plate and crop image to required anatomy (poor practice)	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
Use of CR 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 a grid with too low a line density	Possible decrease	Risk of aliasing artefacts
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 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 the 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

Table 2.4. *(continued)*

Action	Effect on dose	Influence on image quality or diagnostic information
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

2.5. Image Post processing

(70) CR workflow can be divided into exposure of the CR plate, the read-out process in the CR 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 DR the image data is recorded at the time of exposure, eliminating the readout step.

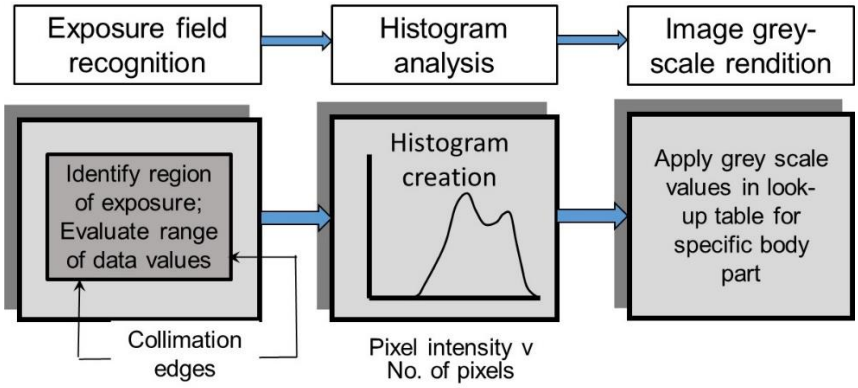
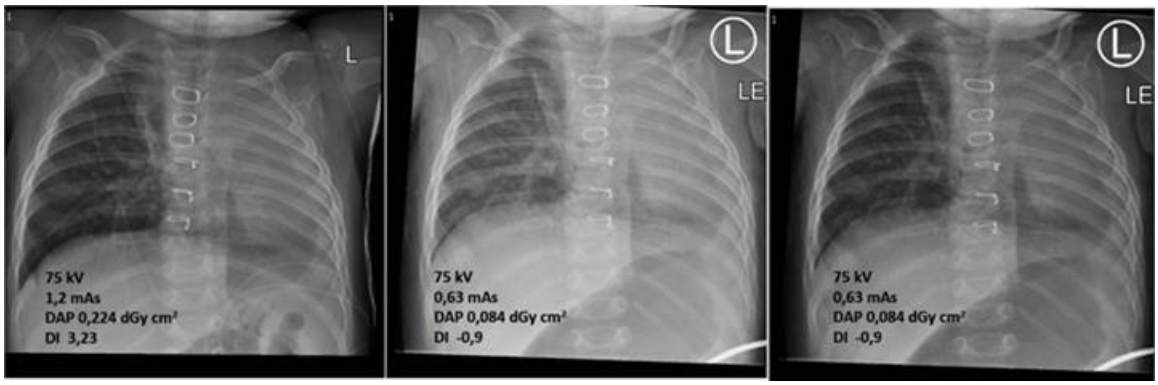


Fig. 2.6. The basic steps in processing of digital x-ray image (Colin Martin, University of Glasgow)

(71) Manufacturers have proprietary post processing algorithms that include contrast enhancement; spatial frequency or edge enhancement; and multi frequency enhancement in which different spatial frequencies are manipulated separately. CR systems have numerous pre-installed look-up tables (LUTs) linking grey levels to exposure for different anatomical regions (e.g., head, chest, etc.). The appropriate LUT must be selected before the image is delivered to PACS for reading, and use of an inappropriate selection may lead to a poor quality image that has little value for diagnostic purposes.

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



a b c

Fig. 2.7. Windowing adjustment example. Paediatric chest images in NICU (a) with a higher mAs dose, and b) with a lower mAs dose, and c) where windowing has been used to improve contrast of the lower dose image (Dean Pekarovic, University Medical Centre Ljubljana, Slovenia).

(73) Before an image is archived, contrast and edge enhancement can be adjusted to achieve better visibility of the required anatomy or pathology. Although these tools can improve an image, they do not replace appropriate choice of the exposure parameters and well-adjusted indication specific post-processing.

(74) 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 PACS for image review. This will aid selection of the most appropriate LUT and can help to identify lower dose options that will give a similar quality image. 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.

(75) There are pitfalls in over application 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.

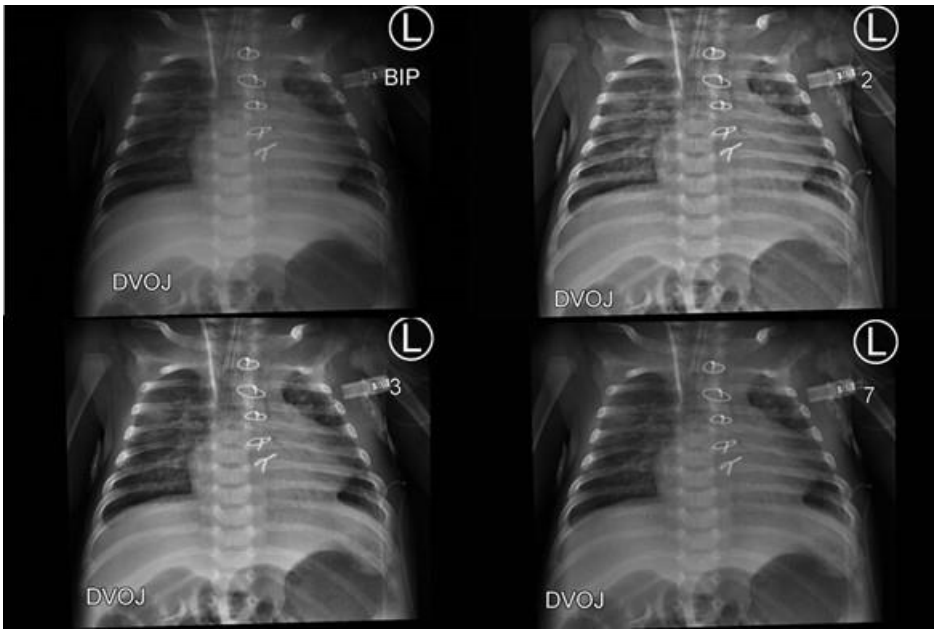


Fig. 2.8. Chest radiographs of the same patient with similar exposure parameters, on which different post processing algorithms and lookup tables (LUTs) have been used. (Dean Pekarovic, University Medical Centre Ljubljana, Slovenia).

2.6. Optimisation of the imaging workflow

(76) 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 clearly defined to enable them to work together to achieve the objective. The basic steps are discussed in detail in Section 5.2.1:

(77) 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 quality assurance and improvement tool to assist radiographers that perform portable DR and to reinforce the safety practices.

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Box 2.4. Safety steps to image and verify for your patient (adapted from Image Gently)
Prior to Starting the Exam 1. Patient name selected from the worklist 2. Patient properly identified (two-point verification) 3. Appropriateness of request checked 4. Explained the exam to patient/parent 5. Verified Last Menstrual Period/pregnancy status if appropriate
Image Capture During the Exam 1. Beam body part image receptor aligned, SID checked, use of grid determined 2. Patient positioned and body part measured, cassette positioned (CR only) 3. Beam collimated 4. Technical factors selected 5. Shielding and markers placed 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 (CR only) 2. Images displayed and reviewed; identification confirmed 3. Image quality reviewed 4. Exposure indicator/index checked; deviation index compared to target exposure index 5. Image reprocessed or repeated as necessary
Following Completion of the Examination 1. Post-processing performed only if necessary 2. Exam verified and images archived to PACS for reporting

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2.7. Basic quality assurance (QA)

939 (78) Acceptance testing and commissioning are crucial to ensure equipment is performing
940 optimally. Before any imaging system is first used, an acceptance test should be performed to
941 verify image quality, dose, and compliance with the manufacturer's specifications (ICRP, 2022).
942 After commissioning, medical physicists and radiographers should work together to establish
943 a local QA and management programme involving QC and other tests on different components
944 of the system with defined tolerances and frequencies for all tests performed (IPEM, 2010;
945 AAPM, 2006, 2015).

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2.7.1. CR systems

(79) The acceptance test for a CR 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). CR plates and the CR reader in every x-ray room should be checked, and a system of daily reporting of any differences in the imaging chain, which should be investigated immediately. CR plates that have not been in use for more than 24 hours should be erased before use. There are two types of erasing, the fast one is used on a daily basis, but periodically a deep erase on all plates is recommended.

(80) Any cassette that has not been used for some time should be cleaned with a dedicated cleaning fluid before being inserted into the CR reader. Too frequent and inappropriate cleaning of the screens can discolour the phosphor and create artefacts on the images. CR 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.

(81) CR plates can be damaged during the readout process by dust or particles of wet plaster (from patient castes). When artefacts on CR plates are recorded during QC tests, it is not necessary to withdraw the CR plate from use. If they are near the edge and should not jeopardise the diagnostic quality of the image, it is enough 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 only for pelvic or abdominal imaging and instruct other radiographers to avoid paediatric or adult chest imaging where artefacts will be more visible. This can extend the lifetime of a CR plate which can be important if funds are limited.

(82) The exposure index for CR plates is linked to the SNR performance and this will deteriorate gradually over time and 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 CR plates are introduced, they should be put through a quick and simple acceptance test to inspect and check the plate quality.

(83) QC is achieved through exposures of test objects or phantoms, containing usually simple patterns, to assess the whole imaging chain (EC, 2004; ICRP, 2022). 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. DR systems

(84) Performance measurements for DR image receptors are similar to those for CR 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, and checking and controlling performance of different components of the system, such as AEC performance, tube output, and detector homogeneity (AAPM, 2006).

2.8. Approaches to Optimisation

(85) 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. Facilities in level D, 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 QC/QA tests on all digital x-ray units and CR 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
- 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 dose monitoring system for an organisation wide on-line 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. Establishment of more comprehensive and consistent optimisation based on this.
- 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

(86) **Key messages 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.**
- **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.**
- **Quality control (QC) programmes should be established to evaluate performance of all exposure modes relating to selection of options that are optimal for specific imaging tasks.**
- **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.**
- **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 procedure and its optimal performance should be carefully balanced for each individual patient and each clinical situation.**
- **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.**
- **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 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 established to promote optimisation through review of common fluoroscopic procedures.**

3.1. The evolution of fluoroscopic techniques

(87) 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.

(88) This section deals with optimisation of all aspects of the use of fluoroscopy, including interventional radiology and cardiology and digital subtraction imaging. 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.

(89) 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).

(90) Fluoroscopy was initially a technique used only by radiologists in diagnosis, but this changed with the development of fluoroscopically guided percutaneous procedures to its current 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 (US, CT, MRI) and minimally invasive alternatives (endoscopy), the fluoroscopically-guided interventional (FGI) procedures have increased by type, number and complexity. The estimated annual total of about 24 million interventional radiology procedures in the latest UNSCEAR report represents a sixfold increase from the 3.6 million procedures in the earlier report, while the collective dose has risen by a factor of eight. The increased use is due to their relatively low invasiveness and risk, faster recovery times, shorter hospital stays and lower cost compared to surgery. 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 of tissue reactions such as skin injuries and cataract (ICRP, 2000b, 2010, 2013a; IAEA, 2010). It is critical that all clinicians receive appropriate education and practical training before undertaking any FGI procedures. The optimisation task in fluoroscopic imaging is far from trivial. It requires appropriate selection of a complex set of technical parameters, tailored to the clinical task, and should start with the establishment of a core team of radiologist, radiographer, and medical radiation physicist properly trained in fluoroscopy. When FGI procedures involve clinicians and/or surgeons, nurses, and anaesthetists, they must understand radiological protection principles of justification and optimisation and undergo both initial education and ongoing training (ICRP, 2009, 2022; NCRP, 2010).

(91) 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.

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

1) Appointing a multi-disciplinary team (medical physicist, radiographer and radiologist/interventionalist) to establish appropriate design features for selection of a fluoroscopy system consistent with the intended clinical uses (Section 3.2).
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).
3) Establishment of a Dose Management QA programme along with the core team to establish and promote optimisation through reviews of common fluoroscopic procedures. (Section 3.8)
4) Applying a comprehensive Dose Management QA programme, including equipment

maintenance and QC tests to verify the equipment performance (Sections 3.4, 3.5 and 3.7|).

5) 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 to the clinical team members. (see 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

Box 3.1. Types of Fluoroscopy equipment

Conventional R/F systems combine fluoroscopy (F) and radiography. These systems have been used for a wide variety of diagnostic examinations such as barium contrast studies of the upper and lower gastro-intestinal (GI) tract although many of these have now been superseded by other 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 GI, gastro-urinary, chest, musculoskeletal and vascular systems. Equipment consists of a patient table that can be tilted from 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 or further from the patient. A variation of the combined R/F system is the remote-control R/F system, which features the opposite configuration of the x-ray tube above the table, and the image receptor fixed under the table.

"C-arm" geometry systems are either fixed or mobile, 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 3D image data and operate as cone-beam CTs.

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 (ADRC) systems and spectral filters. They also allow for digital subtraction, road mapping and other post-processing capabilities. Angiography systems typically also have 3D imaging capabilities extending their use to cone-beam CT acquisitions.

(93) Fluoroscopy systems are manufactured in a variety of configurations allowing optimisation of the system for the intended clinical tasks. The main configurations are a) conventional fluoroscopy systems with the additional capability to perform radiography, b) C-arm systems and c) 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.

(94) 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 image intensifier (II), or a flat panel (FP) detector. It also commonly includes a filter (Box 2.3), 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). The anti-scatter grid should be easily removable, especially when the system is to be used for paediatric patients.

(95) Image receptors for both IIs and FPs are available in a range of sizes, varying from about 10–15 cm up to 40 cm depending on the intended clinical application.

(96) 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 signal to noise ratio (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. With larger and less expensive storage becoming available, some facilities are choosing to capture and store fluoroscopy mode imaging especially for paediatric cases in order to achieve dose savings.

(97) Fluoroscopy/radiography mode is selected on the console, or by the operator at the start of or during the study, and based on the protocols defined in 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.

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

(98) Modern fluoroscopy systems operate in pulsed fluoroscopy and other acquisition modes with several pulse 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. Lowering the pulse rate however 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.

(99) 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 33.44 keV) or iodine (at 33.17 keV). Other filter materials like gold and tantalum are also used to modify the spectrum.

(100) 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 SNR. Real dose reductions of around 22% have been reported in the past (Aufrichtig et al., 1994; Mahesh, 2001).

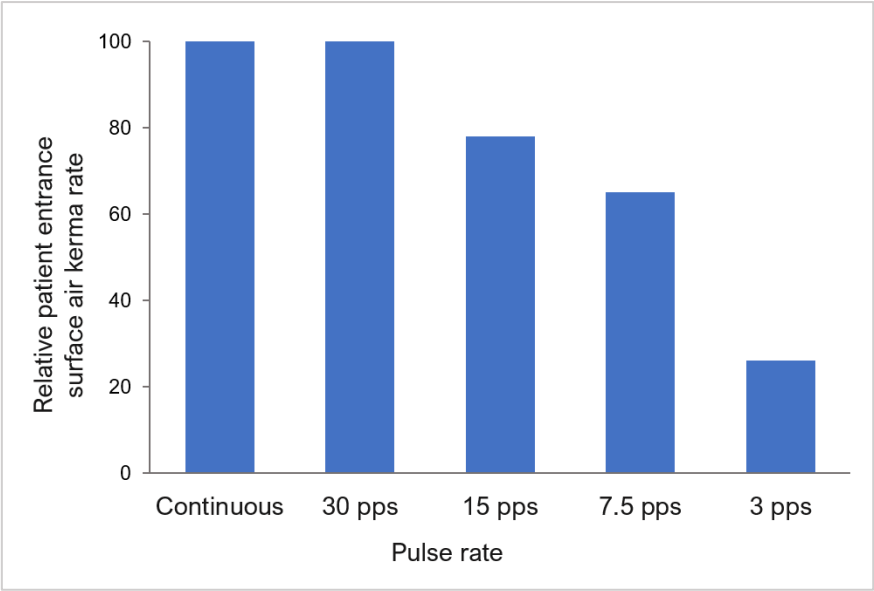

Fig. Effect of pulsed fluoroscopy on patient entrance surface air kerma rate for constant SNR.

(101) All fluoroscopy systems are equipped with a collimator device to limit the geometric extent of the x-ray field, which might have 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 field of view, 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 since 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.

(102) Modern fluoroscopy systems feature a last image hold (LIH) capability, which is the capture and display of the last acquired frame. Some systems incorporate a Last Series Hold (LSH) feature that can even replace digital runs (Radvany and Mahesh, 2015). These are useful features that reduce the fluoroscopy exposure time and thus patient exposure, by viewing the image details without exposing the patient. The images remain only until the next fluoroscopy exposure (IEC, 2019).

(103) Modern fluoroscopy systems have automatic positioning systems, which reduce the amount of fluoroscopy time required to properly position the system 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).

(104) Fluoroscopy system incorporates an automatic dose rate control (ADRC) sometimes referred to as automatic brightness control (ABC). This device automatically adjusts exposure parameters and the incident air kerma (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 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.

(105) 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. Flat panel-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 of 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

(106) LIH and LSH 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, which should always be the preferred options to reduce patient exposure, instead of recording radiographic images or a cine-series (NEMA 2016; IEC 2019).

(107) 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 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 the scatter dose reaching the eyes (Balter, 2019).

3.3. Exposure configuration and optimisation during commissioning

3.3.1. Imaging features and requirements

(108) Fluoroscopy systems provide a selection of pre-configured examinations and patient specific technical sets (Balter, 2019). Each configuration comprises of 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).

Box 3.3. Example of automatic dose rate control (ADRC) 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 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 a standard (normal), low-dose and high dose (high contrast) curves. As patient attenuation increases the incident air kerma 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 to high-dose mode to provide a higher level of image quality.

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

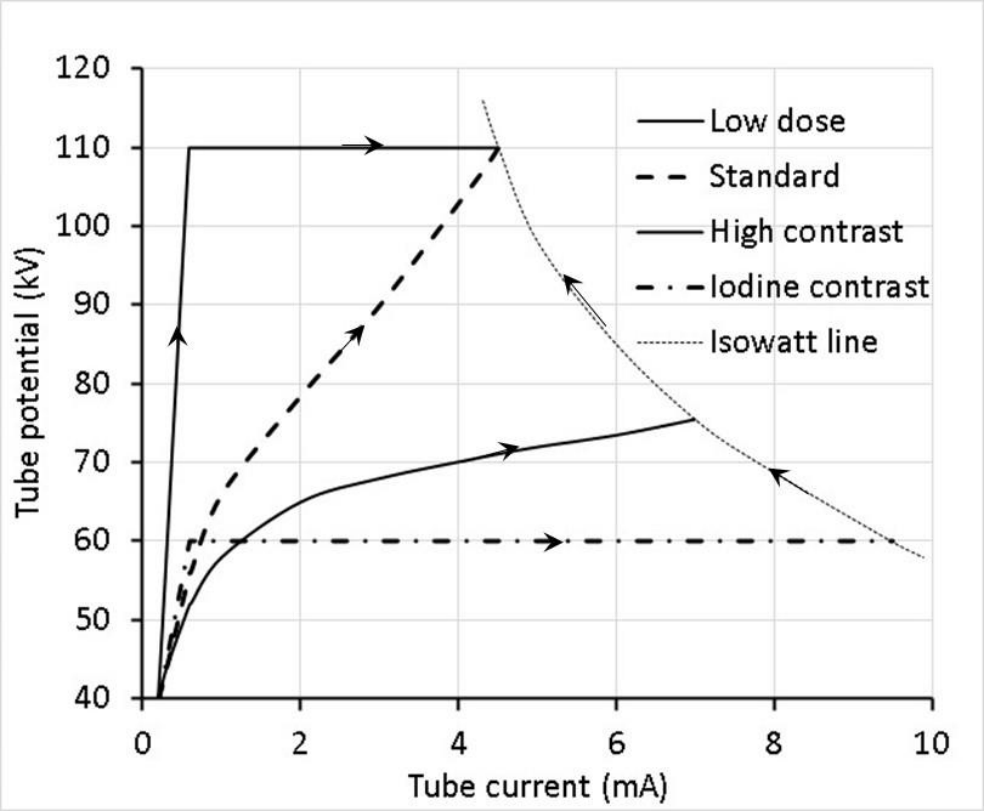

Fig. Example kV vs. mA curves for fluoroscopic exposure modes suitable for different imaging tasks. When the limiting entrance surface air kerma rates at the patient are reached, there are sharp discontinuities as the tube potential is increased and the mA reduced to avoid exceeding the limiting ESAK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

(109) 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 (DSA). 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. It does require however clear understanding of the system features, functions, programme architecture, as well as the clinical requirements and operators' preferences.

(110) Protocol configuration should include consideration of the use of an anti-scatter grid, lower tube voltage, optimal use of collimation and wedge filters, as well as 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, extra bright monitors and optimal viewing distance are also recommended.

(111) For example, a clinical study requiring visualisation of high-resolution images (e.g., small vessels, fine instruments, etc.) requires small focal spot size; smaller source to image detector distance 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 multifrequency 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.

(112) The facility core team should create a variety of selectable pre-defined study protocols and acquisition programmes for the procedures commonly performed with a particular fluoroscopy equipment.

3.3.2. Optimisation of acquisition protocols during commissioning

(113) 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, using standard phantoms and test objects, and representing 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.

(114) Protocol configuration includes proper adjustment of settings customised to the required image quality and dose saving needs for the clinical task. Protocols should be configured to give the required image quality and dose saving needs for the clinical task. This includes the settings for the ADRC system and other programmes for which acquisition parameters are changing.

(115) 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).

(116) One of the most challenging tasks during the system configuration is to set appropriate values of IAK rate at the image receptor in fluoroscopy and radiography modes, for different fluoroscopy dose modes, pulse rates and FOVs (AAPM, 2012; Jones et al., 2014, Stevens,

2021).

(117) The changes in the IAK rate with the fluoroscopy pulse rate and FOV 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 QC programme

(118) Quality control (QC) programmes should be established to evaluate performance of all exposure modes relating to selection of options that are optimal for specific imaging tasks. The requirements of QC programmes are discussed in part 1 of this publication. QC is an essential component of the Dose Management QA programme. Fluoroscopy equipment QC requires a wide variety of tests to be performed with different frequency as described in dedicated guidance publications, and briefly summarised in Table 3.1 (AAPM, 2001, 2012; IPEM 2005, 2010; EC, 2012; IEC, 2019). 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 QC tests for a fluoroscopy system

Elements of QC programme	Parameters to be measured
X-ray source assembly	Accuracy and reproducibility of the tube voltage
	Half- value- layer (HVL)
	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	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 (CBCT) mode if available (EFOMP-ESTRO-IAEA, 2019).	Dose parameters
	Geometry characteristics
	Image quality

(119) 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 (UQCM) for interventional procedures which will allow for an easier and reproducible QC process without vendor involvement and with clinical processing disabled (NEMA, 2018; IEC, 2019). 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

(120) 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 incident air-kerma rate at the patient entrance reference point, as well as their cumulated values (IEC, 2019).

(121) 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).

(122) The Dose Management QA programme should include provision for local audits of patient dose quantities for which local or national diagnostic reference levels (DRLs) are established and for providing patient management/follow-up (ICRP, 2022). However, DRLs are much more challenging to implement for FGI examinations than in conventional fluoroscopy. See Box 3.4 for further explanation.

Box 3.4. DRLs in FGI procedures

Whilst DRLs are very useful for diagnostic examinations they are much more challenging to implement or interpret in the case of FGI procedures because a) such procedures are by definition therapeutic, not diagnostic and b) 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. As a result, 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).

ICRP recommends that even though interventional procedures are therapeutic, the term DRL is retained for use in IR since their purpose is to provide a tool for optimisation and the adoption of a different nomenclature is likely to result in confusion. (ICRP, 2017) The publication does however 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. Other quantities that can possibly be used are reference air kerma ($K_{a,r}$) (IEC, 2020) (also referred to as the cumulative air kerma (CAK) at the patient entrance reference point, fluoroscopy time and the number of radiographic images obtained as part of the procedure. 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.

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 interventional procedures, and preferably the data from all interventional procedures performed (not just from a limited sample) should be collated.

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

3.6. Skin dose monitoring and alert levels

(123) 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 work with attention and apply the proper 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 the peak skin dose (PSD) value (Box 3.5).

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

(125) 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; or stent placement; complex biliary intervention, complex, multilevel vertebral augmentation procedures (including vertebroplasty and kyphoplasty) (ICRP, 2000b, 2010, 2013a; Stecker et al., 2009; Jaschke, et al., 2020).

(126) PSD can be measured directly using different types of dosimeters or calculated from measure 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.

(127) The Dose Management QA programme should include an element in which dose values are monitored throughout the clinical procedure. 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 appropriate 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).

(128) 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 and management of tissue reactions. Table 3.2 shows trigger levels as suggested by the international web-based voluntary and anonymous reporting system for fluoroscopy guided interventional procedures SAFRAD (SAFety in RADiological procedures) of the IAEA. SAFRAD aims to collect information about procedures exceeding trigger levels and define more realistic trigger dose indicators for different types of interventional procedure.

Box 3.5. Measurement, calculation, and estimation of PSD

Measurement: 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, MOSFET radiation sensors, or scintillation dosimeters (Vano 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 around 15–20%, if care is taken for proper calibration and measurement conditions (McCabe et al., 2011; Farah et al., 2015; Greffier et al., 2017). This method is however 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, 2009).

Calculation: PSD can be calculated from the measured dose quantities, geometry and exposure parameters taken from the RDSR data or other types of dose report and a Medical Physicist should be involved in making such assessments (Jones et al., 2011, 2012). The accuracy of the method depends on several factors, including the calibration accuracy of dosimetric equipment, accuracy of information reported in the DICOM header and proprietary dose reports, accuracy of dose quantities (P_{KA} and $K_{a,r}$) 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 (Jones et al., 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 the 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 2D or 3D 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 FGI procedures, with visual presentation of the cumulative results of colour skin dose mapped onto 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 the operator awareness and for enhancing patient safety during FGI procedures (Wilson et al., 2016; Ichimoto et al., 2018)

Estimation: If no means of measurement of PSD is available, reference air kerma, $K_{a,r}$ and P_{KA} can be monitored, and alerts set for these quantities. $K_{a,r}$ is the best predictor of the 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, since 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.

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 SAFRAD)

Dose parameter	During the procedure		Post-procedure
	First notification level	Subsequent notification level (increments)	Trigger level for patient follow-up
Peak skin dose (PSD)	2 Gy	0.5 Gy	3–5 Gy
Reference air kerma (Ka,r)	3 Gy	1 Gy	5 Gy
Cumulated air kerma area product (P_{KA})	300 Gy cm^2*	100 Gy cm^2*	300 Gy·cm^2 (cardiac and neuro interventions) 500 Gy·cm^2 (others)
Fluoroscopy time	30 min	15 min	60 minutes

* Assuming a 100 cm^2 field at the patient's skin. The value should be adjusted to the actual procedural field size (Stecker et al., 2009).

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

(129) 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 one day; repopulation of cells can take several months. Therefore the proper timing of a procedure and its optimal performance should be carefully balanced 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

(130) When a complex FGI procedure is proposed, patient medical and radiation history should be reviewed, and the procedure appropriately planned. Previous diagnostic and therapeutic procedures involving the use of ionising radiation should be reviewed. If necessary, 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, and where imaging is needed a preference given to ultrasound or MRI, to avoid unnecessary use of fluoroscopy during the procedure.

(131) 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, on the length of time left between repeat procedures (Angioplasty or other) relating to the patient's clinical condition, and on methods for identifying areas of previous exposure in order to assist the minimisation of risk where appropriate.

(132) Departments performing FGI procedures should develop a standard checklist to identify patients at higher risk and should have a written form to educate the patient and obtain written consent before the procedure (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.

(133) Patients at increased risk for skin injury include obese patients (e.g., with body mass index greater than 30), 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 interviewed for previous or current skin reactions. All visible skin changes should be marked, so that their locations can be seen on the fluoroscopic image. 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 et al., 2019).

(134) 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 conceptus dose can exceed 10 mGy which include uterine embolisation, ovarian vein embolisation, and endoscopic retrograde cholangiopancreatography (Dauer et al., 2012).

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 human cancer.
- Depending on the complexity of the procedure, a substantial amount of radiation may occasionally need to be used. This could carry a risk of temporary skin injury or hair loss, but any more severe radiation effect is very unlikely.

You (or your family) will be advised if substantial 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_____

3.7.2. During the procedure

3.7.2.1. The team approach

(135) 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. In addition to the main operator who has the primary responsibility for the procedure outcome and for the 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 a radiation dosemeter; and considering the use of alternative image guidance such as ultrasound.

(136) Good practice is for the fluoroscopy team to include a dedicated radiographer to operate the equipment controls, especially when complex FGI procedures are performed, although this will be done by radiologists or cardiologists in some countries. In cases when the controls are operated by physicians 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, and at the same time select 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.

(137) Other team members should also play a part in optimisation of a procedure, e.g., a nurse or radiographer can be responsible for proper positioning of the radiological protection screens, another team member should monitor dose factors and notify the operator when pre-defined levels are reached. Regardless of who operates equipment, the roles should be pre-defined, functions optimised and the team 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. An example of a checklist including all decisions about a procedure can be reviewed at (Image Gently, 2022b).

(138) 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. Radiological protection shields and individual protective equipment should be properly selected and properly used, as recommended in *Publication 139* (ICRP, 2018b).

(139) A successful procedure is reliant upon patient cooperation. Patients should be briefed prior to the commencement of the procedure 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 by balancing the risk of sedation and the risk of compromised image quality and procedure outcome.

(140) 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 needs 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

(141) 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

(142) 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 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 the geometric blurring.

3.7.2.3. X-ray beam projection and collimation

(143) X-ray beam projection and angulation should be selected to provide the required anatomical visualisation but 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 ADRS when object thickness is increased. The use of steep angulations increases patient dose, passing through thicker more lateral sections of the body, 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 during the procedure by modifying the C-arm angulation, to reduce peak skin dose and avoid skin injury.

(144) 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 a possible overlap of the radiation fields from different projections, thus helping to keeping the peak skin dose 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

(145) 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 physician 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).

(146) 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 thicknesses is less than 10 cm.

(147) 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, and to require the operator 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.

(148) 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 LSH function should be used and storing of the last fluoroscopy loop instead of acquiring radiography or cine images.

(149) Box 3.7 provides summary 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.

Box 3.7. Practical techniques to reduce patient dose.

Fluoroscopy dose

- Use a low-dose-rate fluoroscopy mode when possible
- Use a low-pulse-rate fluoroscopy mode when possible
- Remove the grid when performing procedures on small children and thin adults (<10 cm abdominal thickness)
- Use the lowest-dose mode for image (cine) acquisition that is compatible with the required image quality
- Minimise fluoroscopy time – consider ultrasound to guide devices and observe motion
- Use the last-image-hold function for image store and review, when possible, instead of image exposure or using fluoroscopy
- When possible, use 'last series hold', also referred to as 'video loop', if available instead of performing a cine run
- If available, use a stored fluoroscopy loop for review instead of using fluoroscopy

Cine dose and DSA

- Minimise the number of cine series
- Minimise the number of frames per cine series
- Never use cine as a substitute for fluoroscopy
- Sometimes cine runs can be replaced by last screen hold

Other factors

- Collimate the radiation beam to the area of interest
- Use accurate collimation for protection of the gonads, rather than gonad shields
- Use virtual collimation if it is available
- Use wedge filters when they are 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
- Remember that for large patients, and also for steeply angulated projections, the dose to the patient increases substantially

Monitoring dose

- Pay attention to the patient radiation dose display in the procedure room
- If the patient has had 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 peak skin dose (PSD) or 5 Gy cumulative air kerma ($K_{a,r}$)

(150) If conventional image intensifiers 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.

(151) 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.

(152) In some minimally invasive vascular and non-vascular interventions such as in peripheral insertion of central catheter (PICC) placement, 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 only moments when better image quality is needed to localise the object of interest or monitor the procedure development.

3.7.3. After the procedure

(153) 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 monitoring software systems storing dose information in a database can enable more powerful analyses to be performed (Fernandez-Soto et al., 2015; ICRP, 2017; Vano et al., 2022).

(154) Departments should establish a programme for follow-up of patients when any of the pre-defined trigger values described in Section 3.6 is exceeded. It is likely that some skin injuries are missed or mis-diagnosed because of lack of follow-up. The operator 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 might have received a high skin dose could be marked.

(155) 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. Examples of post-procedure patient discharge instructions for high dose procedures is given in Box 3.8. Patients who have not previously notified the operator 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.

(156) If a skin injury is suspected, the interventionalist 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 SAFRAD). In addition, it is recommended that sites where interventional procedures are performed should establish a team that includes a physician, medical physicist and radiographers to review protocols in cases when the patient skin dose exceeds certain

preselected levels.

3.8. Dose management QA programme

(157) As outlined throughout this chapter the development of a successful Dose Management QA programme is an essential part of radiological protection and optimisation (see Section 3.7). 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 established to promote optimisation through reviews of common fluoroscopic procedures. In addition to the equipment selection, facility design, maintenance and QC tests discussed in Section 2 of *Publication 15X*, for fluoroscopy guided procedures, QA should include additional attention to the following components (ICRP, 2013a, 2018b, 2022):

- 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.
- Clinical follow-up for high patient radiation doses.
- Image quality and procedure evaluation.
- Reporting and QA for unintended or accidental exposures.
- Training in radiological protection (RP) ethics, teamwork, safety culture, communication

(158) 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 ICRP (2022): 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 properly used.
- 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 ADRC programmes available for different anatomic regions.
- ADRC settings for different modes and anatomical/clinical programmes tested, adjusted and baseline values of IAK rates at the image receptor set at commissioning.
- Lowest dose rate fluoroscopy mode set as default.
- DSA function available for FGI vascular procedures.
- Regulatory limit for the maximum patient ESAK rate met at commissioning.
- Last image hold function available and used.
- QC tests to characterise system performance carried out at least annually by a qualified medical physicist.
- Regular constancy checks performed by a local qualified staff, e.g., physicist / radiographer / x-ray engineer
- Dose display available and report of cumulated values for FGIs.
- Verification of calibration of dose displays performed as a part of QC.
- Local audits of patient dose quantities 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 and with clinical history of patient, including pre-procedure diagnostic imaging and information on all previous FGI procedures available in the Electronic Medical Record (EMR).
- 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.

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Box. 3.9. ***(Continued)***

B: Intermediate ***(continued)***

- 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" are available and used.
- Store and replay function available and used.
- Large extra bright image monitors utilised for FGI procedures.
- CBCT 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 physician 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 monitoring software 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

(159) **Key messages in this section:**

- **Protocol optimisation can result in significant dose reduction but depends on appropriate selection of scanning parameters and an understanding of the interdependence of the exposure parameters.**
- **Lower noise levels are required for imaging thinner patients because of the absence of adipose tissue between organs, particularly when viewing low contrast anatomy.**
- **Thinner CT slices enable versatile volumetric 3D 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, but the noise level will be higher which is acceptable if the final reviewed image data has sufficient image quality.**
- **Tube-voltage reduction may enable radiation dose reduction by improving the CNR for iodine contrast studies, but typically involve a compensatory increase in tube current to reduce the noise level to achieve acceptable clinical image quality.**
- **Iterative reconstruction (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 adequate 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.**
- **For cardiac imaging CT scanners can be set up to trigger scans at pre-selected phases of the cardiac cycle determined from the 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 ones that are for urgent indications. The level of image quality, exposure factors, slice thickness, pitch, filters, and the need for iterative or deep-learning based reconstruction should be agreed among the professionals involved.**
- **Scan protocols should be reviewed periodically and protocol development be a continuing process with measurements being made of the impact of changes. New protocols should be tested against old ones, and practical assessments made on phantoms if required.**

4.1. The increasing use of computed tomography

(160) Since the first clinical images in 1971, computed tomography (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 a greater potential for identification of abnormal pathology and changes in tissue structure. However, these additional capabilities are usually related to 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, 2019). Moreover, the number of CT scans continues to increase in many countries with the demand for additional clinical information provided by 3D volumetric image data and post-processing (Dovales et al., 2016; Bly et al., 2020). Wide variations in doses 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; Epko 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, a 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 an adequate dose management as part of the QA programme for CT system resources. 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 (Kanal et al., 2017; Matsunaga et al., 2019; Vassileva et al., 2015).

(161) As with other imaging equipment, when a new CT facility is set up or an older system replaced, selection of the appropriate scanner should be carried out by a multi-disciplinary team of radiological professionals (ICRP, 2022). 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).

(162) The next step is protocol optimisation, potential dose reduction, with CT depends 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).

(163) 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 (ICRP, 2022; ACR, 2022). The impact that exposure parameters have on patient dose or potential issues on the 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 physicist in measuring, analysing and interpreting these test results combined with the clinical experience of the radiologist 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).

Box 4.1. CT dosimetry quantities (ICRU terminology given in Annex A)

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

CTDI: The 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 the 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.

$CTDI_{vol}$: The CTDI measured in standard polymethylmethacrylate (PMMA) 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 $CTDI_c$ and periphery $CTDI_p$ 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 volume averaged CTDI ($CTDI_{vol}$) that is displayed on scanner consoles (Section 4.2.4).

DLP: The $CTDI_{vol}$ can be multiplied by scan length to derive the 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 which varies greatly, 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) and it is planned that these will also be displayed on scanner consoles in the future.

4.2. The CT image

4.2.1. CT numbers, noise, slice thickness and contrast

(164) 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 at −1000 HU.

(165) 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 contrast to noise ratio (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.

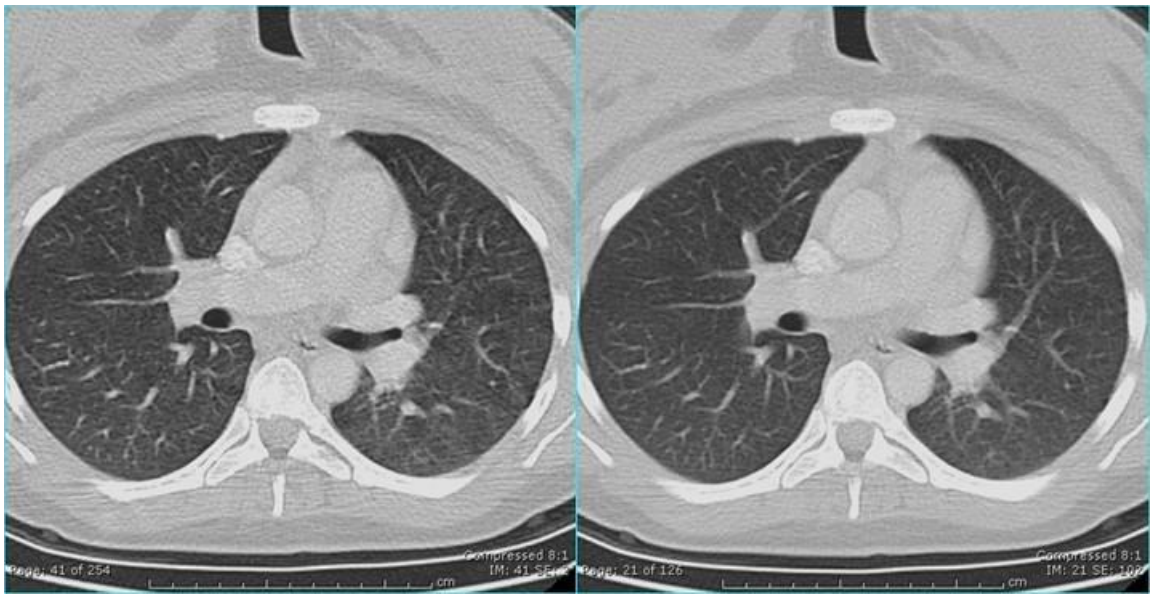

Fig. 4.1. CT chest images with contrast taken at 120 kV. The image on the left is with the standard exposure and the one on the right has double the mAs. The clinical image quality difference between the two images is slight and there is no gain in diagnostic information from the higher exposure. CT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

(166) 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 to 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 in Section 5.2.4).

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

(168) If the thickness of the reconstructed image is reduced, a higher mAs will be required to provide the equivalent signal to noise ratio (SNR) within the width of the thinner slice. In modern CT scanning, image data are often acquired with thin slices that have roughly the same voxel dimension in the x, y and z directions (i.e. isotropic resolution). This enables subsequent multiplanar reformats (MPR), modality image co-registration, annotation, and/or 3D review to be performed by radiologists. These thin source image reconstructions will have higher image noise levels than are seen in the final reformats with thicker slices or 3D 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'.

(169) CT contrast media typically involve iodine-based compounds (ACR, 2021). The injected intravenous (IV) 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 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 (CTA) to be an effective method of optimisation. CTA 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

(170) 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), postero-anterior (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 field of view 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 and even scanner software version. It is important to be aware of the SPR recommendation because SPR has a direct effect on the automatic tube current modulation (ATCM) and automatic tube voltage selection (ATVS) performance, and as a result on patient dose and image quality.

(171) During routine scans of the brain, the gantry may be tilted to reduce the radiation dose to the eyes and 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 eye lenses in head CT scans can also be implemented by tilting the patient head forward by 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 that 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, the overall image acquisition, and patient acceptance.

(172) 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 overranging, 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 overranging is more relevant in dose optimisation when the exposed organ outside the planned region is radiosensitive (for example the thyroid in head scans of paediatric patients or younger adults) and can be estimated using Gafchromic film.

(173) The radiation exposure to a patient is mainly dependent on the applied dose level (estimated through the $CTDI_{vol}$ and size corrected as SSDE) and the anatomical length of the exposure to the body, including repeat passes through it (measured by the 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.

(174) 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

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

(176) 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 (Lee et al., 2012b). 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.

Box 4.2. Choosing the tube potential for a CT 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 AP and lateral body dimensions in cm (Ranallo, 2013; AAPM, 2022).

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

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.

(177) A lower tube potential will significantly decrease patient dose 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 iodine 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.

(178) 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 automatic tube voltage selection (ATVS) can provide images with improved contrast at reduced patient doses (Mayer et al., 2014).

(179) 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). The shape and composition of the filters varies with vendor and 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 field of view 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

(180) 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, but 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 will give greater additional exposure from overranging for scanners without dynamic collimation (Fig. 4.2).

(181) 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, where the patient size is smaller than in adults, the gantry rotation speed is often set at 0.5 seconds to decrease the chance of motion artefacts.

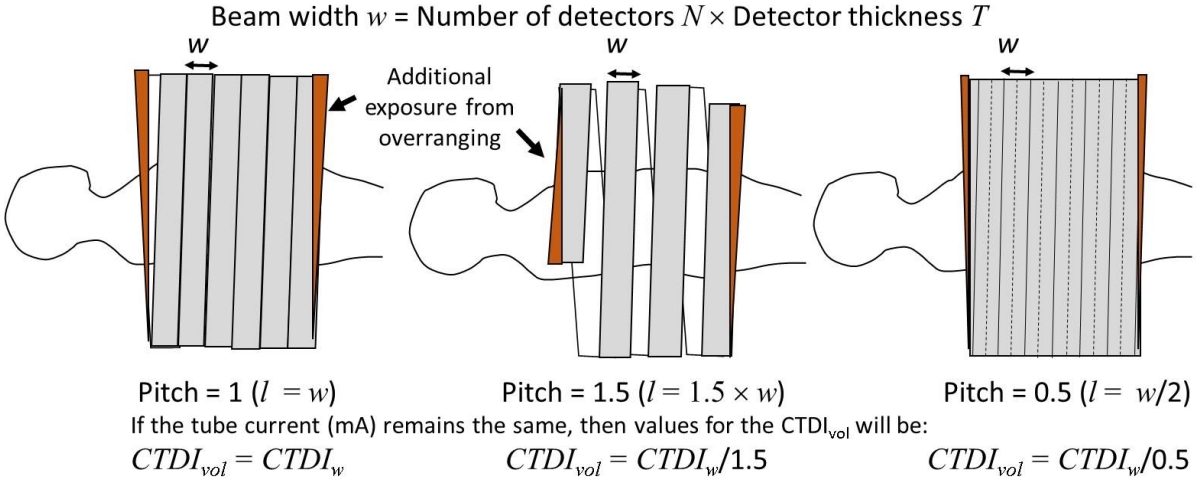

Fig. 4.2. Examples showing the CT beam trajectory for scans with different pitches. The additional partial rotations at the start and end of the scans are required for image reconstruction. Additional parts of the body not being imaged, highlighted by a darker shade, will be irradiated if there is no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

4.3. Image reconstruction

(182) **Filtered back projection (FBP)** is the analytical method used that has long been used for reconstructing CT images. 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. But 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.

(183) **Iterative reconstruction (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. Then, 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 the forward-projection) may require high computing power. Most IR techniques enable the noise level in images to be reduced and help to suppress artefacts.

(184) 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 percentages have 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).

(185) If a scanner has the facility for IR, it should be used when it can improve radiological optimisation by reducing 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).

(186) Iterative reconstruction (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).

(187) Radiologists 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 radiologists at the facility, and any modification in the level of IR and adjustments in exposure level should be made in stages to ensure that radiologists interpreting the images are deriving a benefit from the changes made.

(188) **Deep learning-based image reconstruction or restoration (DLIR)** has emerged as an alternative to FBP and IR. As deep learning is a subset of machine learning, DLIR can also be classified as artificial intelligence (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, DR and DLIR from the same raw-data in CT is shown in Fig. 4.3.

(189) However, all new reconstruction methods and all new techniques together should be appropriately validated 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 is 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.

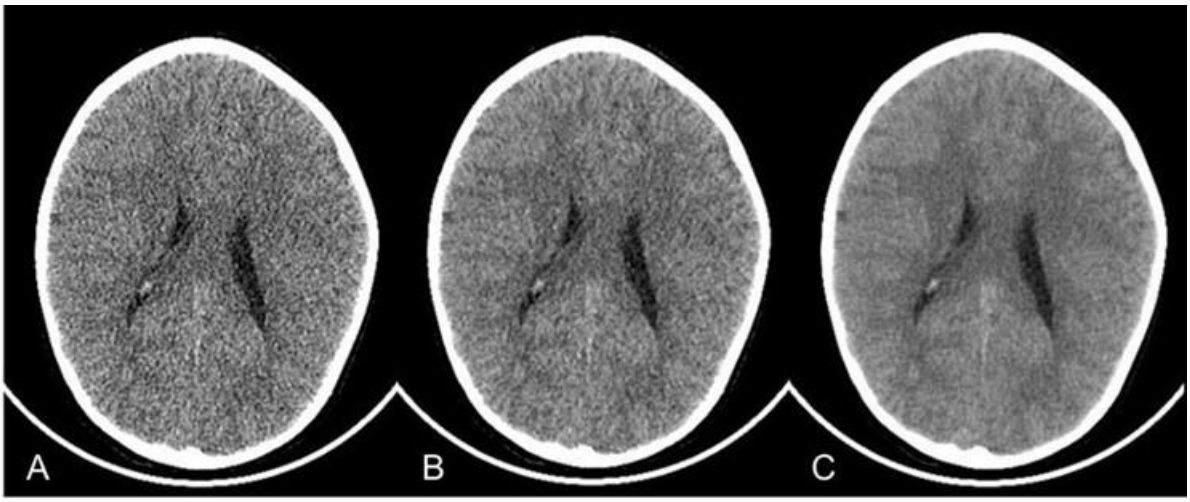

Fig. 4.3. An example of A) traditional (FBP; standard filter), B) iterative reconstruction (ASiR-V 50%) and C) deep-learning based reconstruction (TrueFidelity High) from the same raw-data in a neurological brain scan performed with GE Revolution CT for a 5 years old girl. The scan was performed with single 0.35 s axial rotation with 16 cm z-coverage, 120 kV, 0.625 mm slice thickness, CTDIvol of 20.7 mGy, and DLP of 330 mGy cm. The background noise values (SD in HU) in the images were 9 HU in A, 6 HU in B, and 3 HU in C. Images courtesy of Mika Kortesniemi, HUS Medical Imaging Center, New Children's hospital, Helsinki, Finland.

4.4. Automatic tube current modulation (ATCM)

4.4.1. How it works

(190) For a given tube potential, the tube current determines the number of photons emitted and so 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 automatic exposure control (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 (Mulkens 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.

(191) 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 the 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.

(192) 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 operation of ATCM systems and CT scanner vendors and/or models have slightly different approaches to this.

(193) 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 the 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).

(194) 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 predetermined levels with the strength of modulation being chosen by the operator and the noise level in the image is 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 standard deviation (SD) as the image quality reference, ATCM systems seek to maintain the same noise level throughout a scan, a higher noise level may be acceptable for larger patients to take account of differences in contrast between patients of varying size.

4.4.2. Using ATCM and automatic tube voltage selection (ATVS)

(195) 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.

(196) Because ATCM systems from the various vendors use different control parameters, translation of established protocols between scanners of different type 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 the $CTDI_{vol}$ (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).

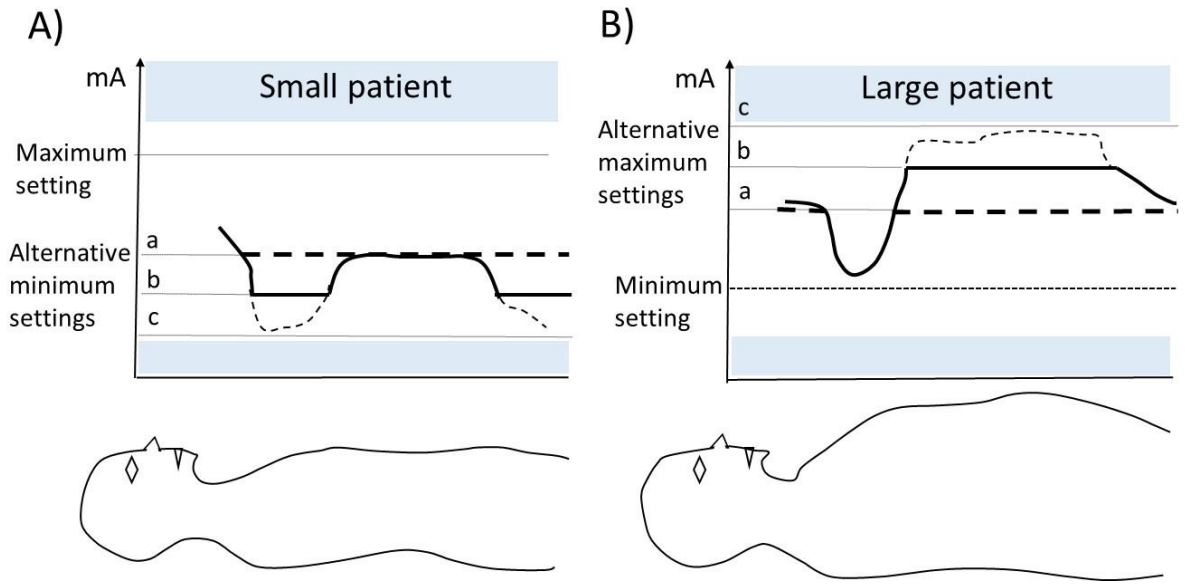

Fig. 4.3. Plots showing examples of the variation in tube current along the bodies of two patients, derived from ATCM operation for which noise has been used as a reference. A) represents a small patient for whom the minimum mA may have been set a) too high restricting the modulation (bold dashed curve), b) at an acceptable level (bold solid curve), and c) too low allowing the tube current to fall to a level whether the image quality may be compromised (fine dashed curve). B) represents a large patient for whom a) the maximum mA setting is too low restricting modulation (bold dashed curve), b) at an acceptable level (bold solid curve), and c) may be too high so that the mA and the 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 (Colin Martin, University of Glasgow).

(197) 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. But for scanner models that use a noise reference, the maximum and minimum mAs settings can be selected by the operator (Fig. 4.3).

(198) 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. 4.3. 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. 4.3A) and doses for large patients are not excessively high (Fig. 4.3B), 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.

(199) 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. Position the patient and QC testing for ATCM systems

(200) 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. 4.4). Since the ATCM calculations are based on an assumption that the patient is centred within the gantry, tube currents selected by the ATCM may be higher or lower if a patient is mis-centred. This issue has been addressed through automatic adjustments in the latest CT models of some vendors (Zhang and Ayala, 2014). Some modern systems allow for small lateral displacements of the table from the console to compensate for patient mis-centring. Lateral displacement can create a similar effect but this does not typically present a problem. The influence of the SPR on ATCM and also ATVS has been evaluated by using phantoms (Kaasalainen et al., 2019) and with patients (Filev et al., 2016).

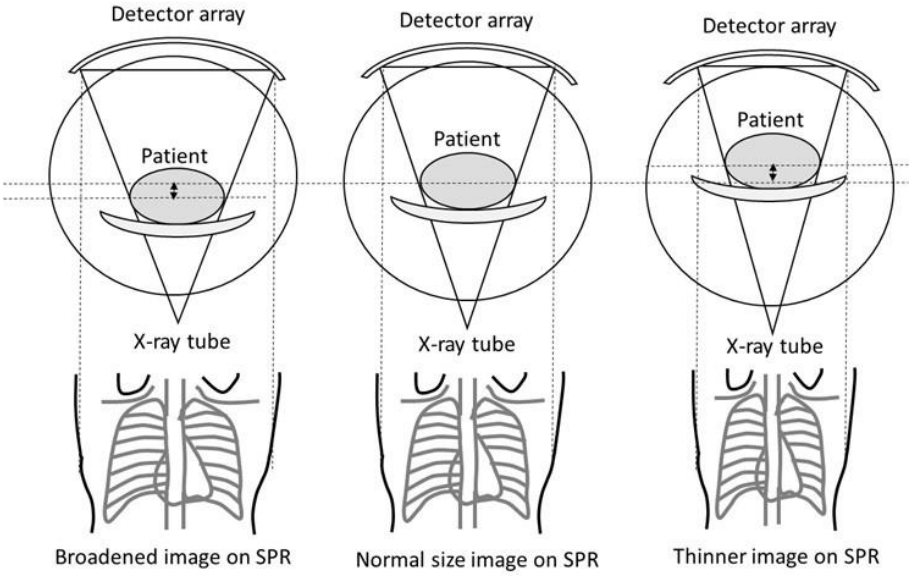

Fig. 4.4. Diagrams showing how height of the couch can affect the apparent patient dimension on an SPR recorded with a PA projection. When patients are lower (left) the image is magnified, while when they are higher (right) the image is reduced. (Colin Martin, University of Glasgow).

(201) Testing of ATCM systems should involve phantoms with both discrete and continual changes in phantom diameter and net attenuation (AAPM, 2019b) e.g. 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 CTDIvol, to be evaluated.

4.4.4. Organ dose modulation

(202) 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 breasts, thyroid, and eye lenses. These options, called variously organ dose modulation, organ-based tube current modulation (DM) or 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). The tube current in the remainder of the rotation may be increased so that the overall radiation dose (CTDIvol) remains constant (Hoang et al., 2012), or an increase in noise level in the image with a lower dose may be accepted (Dixon et al., 2016).

4.5. Other CT technology and procedures

4.5.1. Dual-energy CT

(203) 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). There are basically five methods being applied to modern CT scanners (incorporating energy integrating detectors) achieving this 'spectral energy' or dual-energy CT (DECT) scanning. Scanners may 1) have two x-ray sources; 2) use a single x-ray-source with fast switching of tube potential; 3) use a single-source CT that switches tube potential between gantry rotations; 4) use a single-source CT that splits the incident beam into two halves with different filtration and separate detection in the longitudinal (z) direction, or 5) a single source used with two superimposed detectors separated by a filter, so that different energy spectra are incident on the second detector (McCollough et al., 2015; D'Angelo et al., 2019).

(204) Where two tube potentials are used in DECT, these are typically 140–150 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). 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), organ perfusion and blood pool imaging can be carried out (Zhang et al., 2013; Sun et al., 2018), and characterisation of structures such as urinary stones (Qu et al., 2013). There is also the possibility of generating a 'virtual' non-contrast set of images (Fig. 4.5) from a single scan with contrast to avoid a pre-contrast scan (Graser et al., 2009; Barrett et al., 2012; George et al., 2017; Rajendran et al., 2021b).

(205) 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).

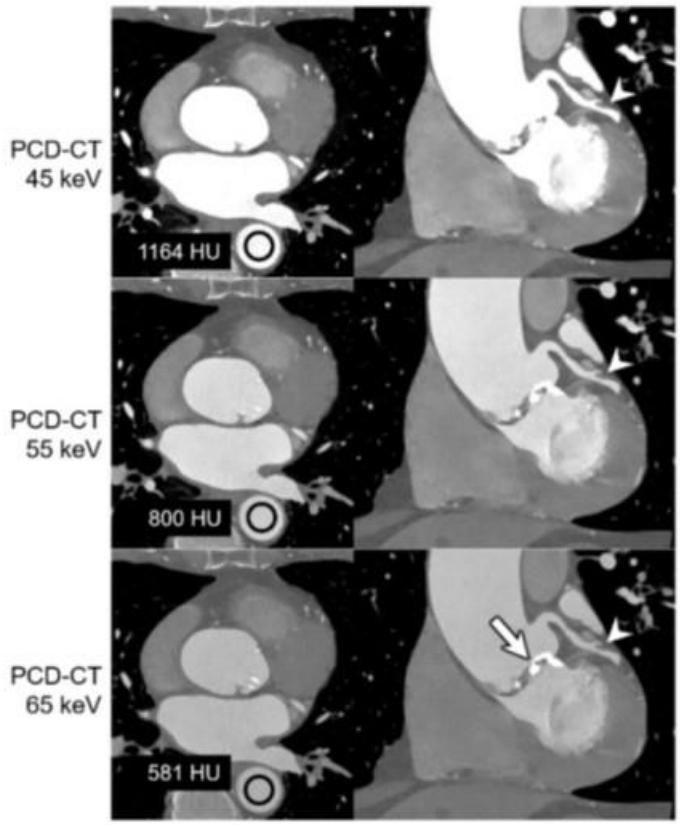

Fig. 4.5. Images from a **photon counting detector** (see 4.5.7) DECT to achieve 66 ms temporal resolution. Axial CT images are shown on the left and oblique coronal images on the right. The multi-energy capabilities allow creation of virtual monoenergetic images (VMIs), which show increased iodine signal (mean HU in the regions of interest). The VMIs added to the inherently higher iodine CNR and provided clearer delineation of the left coronary artery (right hand images). The white arrow in the bottom right image indicates calcification of the aortic valve. 90 ml iohexol contrast was used which was 18% less than for single kV images. (Rajendran et al., 2021b; with permission from RSNA.)

(206) As a summary of the image data point-of-view, spectral imaging with dual-energy or spectral detectors offers additional image representations for diagnostics. These include virtual monochromatic (specific keV level) images, which show increased iodine signal compared to conventional IED CT (Fig. 4.5). DECT also enables the formation of iodine concentration maps and virtual non-contrast images excluding highlighting of iodine filled vessels in contrast enhanced scans (Fig. 4.6), and effective Z images which widens the diagnostic value and optimisation role in CT imaging. 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.

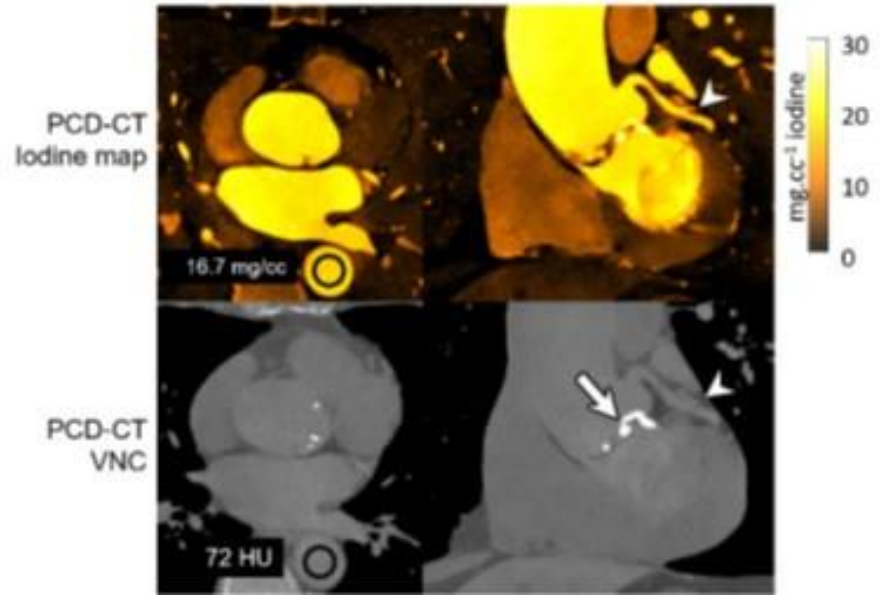

Fig. 4.6. Images derived from the scan data in Fig. 4.5, showing iodine maps with concentration in mg ml^{-1} and the virtual-non-contrast mages used to visualise calcifications having a similar attenuation to the iodinated blood (white arrow bottom right). (Rajendran et al., 2021b; with permission from RSNA).

4.5.2. Cardiac and coronary CT

(207) Studies of the heart and coronary arteries have become common with broader fan beams 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 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 then 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).

(208) The acquisition is usually performed during the diastolic phase to minimise motion artefacts. However, if the pulse rate is above 70, end-systolic phase reconstruction may provide a better temporal window to freeze the cardiac movement as compared to 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).

(209) 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 substantially reduce doses 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.

(210) Additional benefits may be obtained from the use of advanced image reconstruction, deep learning, 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 (a) the identification of hemodynamically significant coronary artery disease, (b) CT delayed-enhancement imaging to detect myocardial scar after myocardial infarction, and (c) measurement of the extracellular volume fraction in non-ischemic cardiomyopathy (Ko, 2019). Paediatric heart rates often remain relatively high, despite pharmacological heart rate reduction (Mortensen and Tann, 2019). However, dual source and wide beam techniques that allow cardiac scans to be obtained in sub-second, single 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. CT perfusion studies

(211) 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 perfusion CT, 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 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 use of incorrect settings by operators who did not understand the potential impact of CT parameter changes on dose.

(212) Procedures with the potential to cause injury should be identified beforehand and steps taken to ensure all settings are satisfactory. Checks can be made on skin dose levels, since the $CTDI_{vol}$ 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 about 1.3 × $CTDI_{vol}$ (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. CT fluoroscopy and guided interventions

(213) CT fluoroscopy is now used to guide interventions combining cross-sectional images or 3D image volumes with almost real-time display. Images at a fixed position are continually updated 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.

(214) Tube currents of a few tens of mA are used, giving incident doses of 2–10 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).

(215) Radiologists 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 CT

(216) Photon-counting CT (PCCT) is a new addition to clinical CT technology with the potential both 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, integrated energy detector (IED) 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 IED 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).

(217) 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 medias. This could allow 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 also in specific scanner designs such as in cardiac and breast imaging (Kalender et al., 2017; Lell and Kachelriess, 2020; Hsieh and Flohr, 2020; Eberhard et al., 2021). PCCT has the potential to dramatically change practices in clinical CT imaging (Rajendran et al., 2021a).

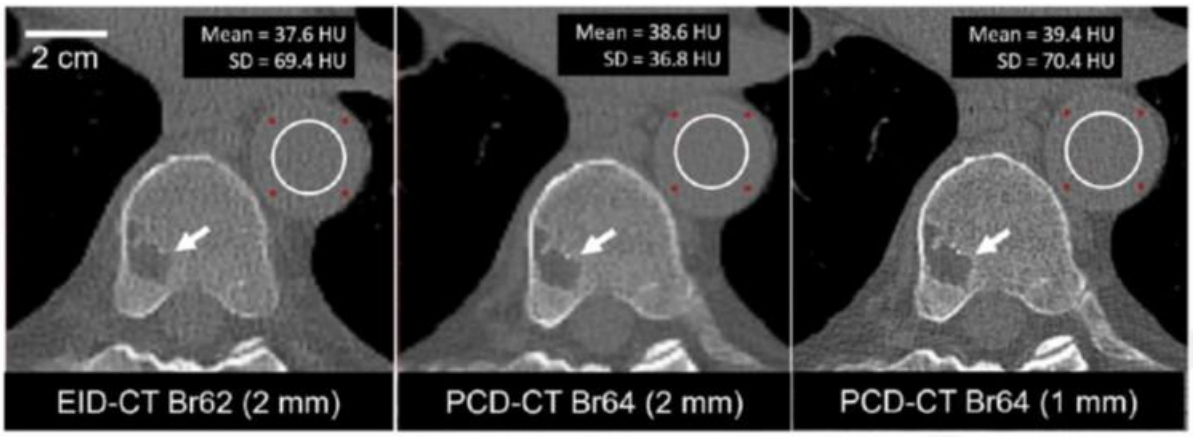

Fig. 4.7. Comparison of images from an IED CT scan (left) and a high resolution PCCT scan (centre and right) for a 74 y old male with multiple myeloma, acquired using the same dose (4.2 mGy) and 2 mm slice thickness. The PCCT showed 47% lower noise (69.4 HU vs 36.8 HU) in the 2 mm images. Use of a 1 mm PCCT slice thickness gave a similar noise level to the IED CT and improved delineation of the vertebral lesion (white arrow). (Rajendran et al., 2021b; with permission from RSNA).

4.6. Development of clinical CT protocols

4.6.1. Establishing clinical protocols

(218) 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 then be reviewed and

revised periodically. The protocols should be developed with input from consultant radiologist(s), lead CT radiographer(s) / technologist(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 more commonly used 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 iterative or deep-learning based reconstruction should be agreed among the professionals involved. The optimisation of protocols for paediatric and pregnant patients are considered separately in Sections 5 and 6. The AAPM have developed a set of protocols for specified diagnostic tasks that can be accessed via the internet (AAPM, 2022).

(219) 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.

(220) Optimisation of any radiological x-ray modality should be based on the proper limitation of exposure range to only the area based on clinical indication and the correctly defined field-of-view (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.

(221) Input is required from all radiologists to determine image quality requirements (Maués et al., 2018). There should be consensus amongst radiologists 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, 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.

(222) 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 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 contrast bolus by using bolus tracking or applying a test bolus will also be important for obtaining satisfactory images.

(223) Exposure factors should be individualised through use of the ATCM 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 technologists, medical physicist, radiologist and vendor application specialist) 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.

(224) 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).

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

Pitch, mA, slice thickness and rotation time

- Be aware of interactions between different parameter settings on your scanner e.g. how ATCM is affected by changes in primary reconstruction slice thickness and reconstruction kernel.
- Compare results of new protocols with original ones, when making any changes. It is recommended to keep a database with separated files recording the historical changes in the protocols (acquisition and reconstruction parameters for each clinical protocol and for each CT system in the hospital, which should be keep up to date 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 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 MPR review at thicker reconstruction and 3D 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 √2. Note that the relationship with dose is not certain with more advanced reconstruction methods (IR and 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.

Box 4.3. ***(Continued)***

Tube potential (see Box 4.2)

- A lower tube potential can improve contrast for smaller patients, and will reduce dose.
- When imaging structures enhanced with contrast media, the iodine CNR can be used as an approximate image quality metric to use 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 the ATCM and ATVS.
- Use appropriate anatomical markers to define scan start and stop positions to ensure consistency.

Iterative (IR) or deep learning (DLIR) reconstruction techniques

- IR or 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.

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Box 4.4. Points to be aware of when setting up protocols (assumes ATCM use)

Setting up protocols for 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 the ATCM works with respect to the particular vendor for your CT scanner is key to achieving proper operation and avoiding potential errors
- Do not choose too high a mAs image quality reference or too low a noise reference for operation of the ATCM
- Establish a standard routine for performing the SPR linked to ATCM (and ATVS) 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 understanding and monitoring of the ATCM operation. Anthropomorphic phantoms can also be an alternative.
- Organ dose modulation reduces tube current for angles where x-rays are incident on sensitive organs (mainly eyes, thyroid and breast) and is an option on modern CT scanners.

4.6.2. Patient dose audit

(225) 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 systems tools. The $CTDI_{vol}$ 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; a size specific dose estimate (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 Radiation Dose Structured Reports (RDSR) for each examination, audits of patient doses are becoming easier to perform (Annex B) (ICRP, 2022). Commercial dose monitoring 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 (Nicol et al., 2016). Recent systems also cover other relevant features of optimisation such as scan protocol and scanner utilisation management features.

(226) There are older scanners still in use in developing countries that do not display $CTDI_{vol}$ and DLP values (Rehani and Vassileva, 2018). Where this is the case the mAs, tube potential, pitch, and scan length values should be recorded to provide an indication of any variation with time. Measurements of $CTDI_{100}$ in terms of mGy/mAs can then be used to derive $CTDI_{vol}$ and DLP values for making comparisons and use in development of protocols (Section 4.6.1).

(227) Median values of dose quantities derived from survey data can be compared with DRLs

(ICRP, 2017, 2022). The form in which data are presented, for example using boxplots or bar charts to compare results with the regional or national DRLs, can assist local staff in understanding the level of optimisation that has been achieved.

(228) 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. Then, 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 then be made as to whether the DLP and $CTDI_{vol}$ are both high, as this can be informative in determining possible causes. 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.

(229) The following paragraphs discuss possible causes of higher doses and Table 4.1 summarises some of the possible causes linked to whether the $CTDI_{vol}$ 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 then 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.

Table 4.1. 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 e.g. kV, mAs (or ATCM) level and thickness of first reconstructed slice
$CTDI_{vol}$ 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 one
$CTDI_{vol}$ and *DLP* both high	Average	Is too low a noise level or too high an ATCM image quality reference being selected?
$CTDI_{vol}$ and *DLP* both high	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 one. Also, check the modulation curves displayed, if they are available.

(230) If the DLP is high, but the CTDIvol is within the normal range, then the scanned region may be longer than necessary. Another common reason for higher values for the DLP is the use of more scan series, as ones may be performed initially without contrast medium, followed by ones 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 the DRL values apply to a single CT scan series and not to the cumulated DLP of the entire examination.

(231) If both DLP and CTDIvol are high, then the scan parameters should be reviewed in detail to determine if they were justified or corrective actions needs 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).

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

(233) 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, then dose quantities CTDIvol, DLP and optimally the SSDE can be plotted against patient diameter (Sookpeng et al., 2014; ICRP, 2017; Kanal et al., 2017; Boos et al., 2018; ACR-DIR, 2022). The optimisation process includes various steps where more demanding analysis techniques that are provided by medical physicists or engineers are needed. The proper use and configuration of dose monitoring systems require dosimetry and statistical knowledge in order to exploit their full potential in clinical use. When configuring and implementing dose monitoring systems, it is important to verify that the DICOM and RDSR are activated and in use whenever possible (Annex B), since these structured reports provide an extensive description of radiation exposures for individual irradiation events. Also, the validation of dose data provided to the dose monitoring 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.

(234) There are many occasions where the 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 done in relevant radiosensitive organ locations in the phantom, to verify the dose performance of the scanners with actual clinical protocols or some allow for the insertion of ionisation chambers. Computational phantoms may be used in more elaborate dose simulations to acquire organ dose estimates and 3D dose distributions. An example of such Monte Carlo dose simulation, providing a 3D heat map of dose levels, is presented in Fig. 4.8.

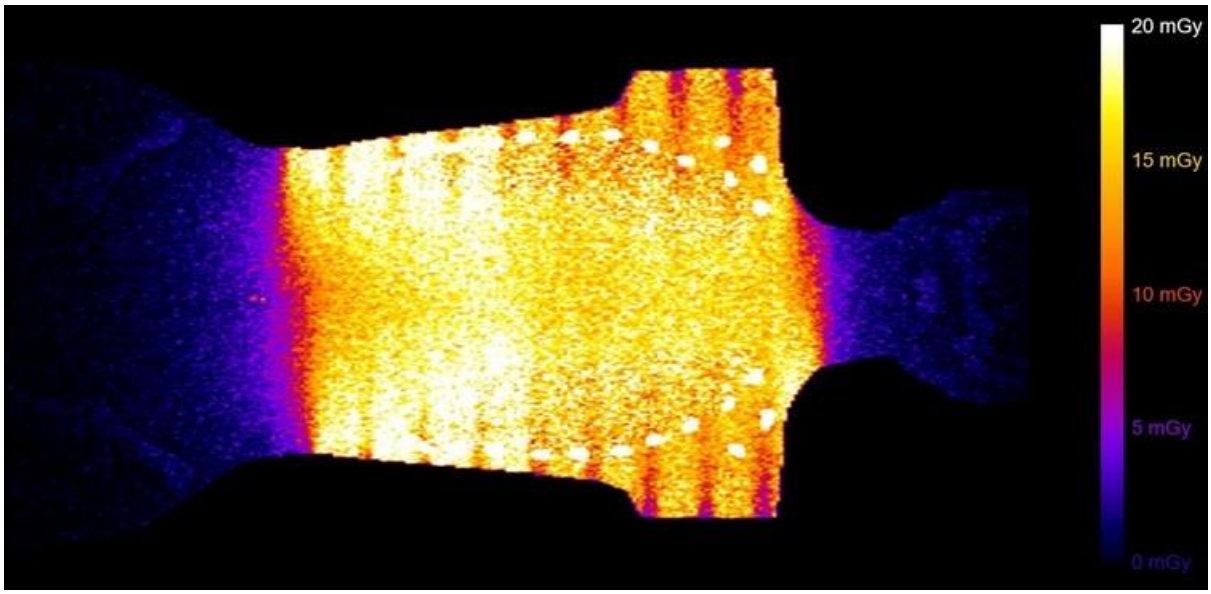

Fig. 4.8. Example of highly heterogeneous 3D dose distribution at a coronal view resulting from a helical chest CT scan performed on an anthropomorphic adult female model. Brighter colours refer to higher absorbed doses in that specific position. Note the scattered radiation which extends outside the primary scanned region. The stripe patterns indicate the helical beam path during the scan. Dose has been calculated with Monte Carlo (MC) 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 Kortesniemi, HUS Finland.

(235) 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 extensively discussed with valuable reference data for medical physicists.

4.6.3. Subjective and continuous assessment of CT protocols: The core team and beyond

(236) The scan protocols once established should be reviewed periodically and changes 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 one 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.

(237) Changes such as the introduction of iterative or deep learning reconstruction 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 carried out to ensure all radiologists interpreting the images find the changes acceptable. Then 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 of established indication specific CT scan protocols. Guidance on the approach to practical optimisation is given in Box 4.5 and general arrangements that relate to facilities at different levels in development of their optimisation strategy are set out in Box 4.6.

Box 4.5. Guidance for CT 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 CT 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 QA.
- 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, 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, radiographers and medical physicists should all feed into protocol development; other stakeholders (clinicians and vendor application specialists) may also add information to the local optimisation process.

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Box 4.6. Optimisation arrangements at different levels of development.

In ICRP (2022) and in the introductory section of this document the range in resources and expertise that are available in different facilities is discussed. This presents significant challenges in setting out steps in optimisation that are appropriate for each facility. In order to provide assistance to users in the development of optimisation strategies for their department, the arrangements that should be in place for facilities at different stages of development are listed below for C: Basic; B: Intermediate; and A: Advanced levels. Facility staff and managers should use these lists as a guide to reflect on the arrangements that are already in place and identify those that it would be appropriate to focus on for their next stage of development. Facilities in Level D, still in the very early stages of developing optimisation should consider arrangements within level C: Basic group that they need to put in place.

C: Basic Level

- Requests for CT scans include reason for referral and clinical history of patient.
- CT radiographers trained by vendor applications specialist.
- 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.
- 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, IR implemented for selected procedures with adjustment of exposure factors, after agreement with radiologists.
- Acknowledgement of dose display and using DRLs (published or national) at least for the most general examinations (head, chest, abdomen).
- Regular (daily tube wam-up and air calibration) constancy checks performed by radiographers (QC).
- CT scanner QC tests to characterise scanner performance carried out regularly, at least annually.

B: Intermediate Level

- Comprehensive scan protocols available for a wide range of clinical indications encountered regularly and agreed by all radiologists.
- 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 CNR evaluation.
- Protocols optimised through careful choice of exposure factors.
- Utilisation of specific scanner features for improved optimisation and patient safety.

Box 4.6. ***(Continued)***

B: Intermediate Level ***(Continued)***

- ATCM settings specified based on patients' clinical conditions and sizes.
- ATCM and ATVS 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.
- Iterative or deep learning reconstruction 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 Level

- Use of advanced technology and software for optimisation including IR or deep learning reconstruction, 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, 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 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.

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5. PAEDIATRIC PROCEDURES

(238) **Key messages in this section:**

- **Paediatric protocol optimisation requires an understanding of the clinical indication, patient size, the ability of the patient to cooperate, and alternative examinations available locally to answer the clinical question.**
- **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.**
- **Adopting a graded 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 continuously improved.**
- **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.**
- **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 4 y, 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-old. 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, last image hold, and pulsed fluoroscopy on the lowest possible setting.**
- **The optimisation core team (radiographer, medical physicist and radiologist), should share bi-directional learning with clinicians, families, and other stakeholders. They should review imaging protocols periodically to implement best practices.**

5.1. Requirements for imaging paediatric patients

(239) 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 of imaging protocols) to be followed when imaging these patients. An important approach to improving the radiological protection and the imaging outcomes of children is by 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).

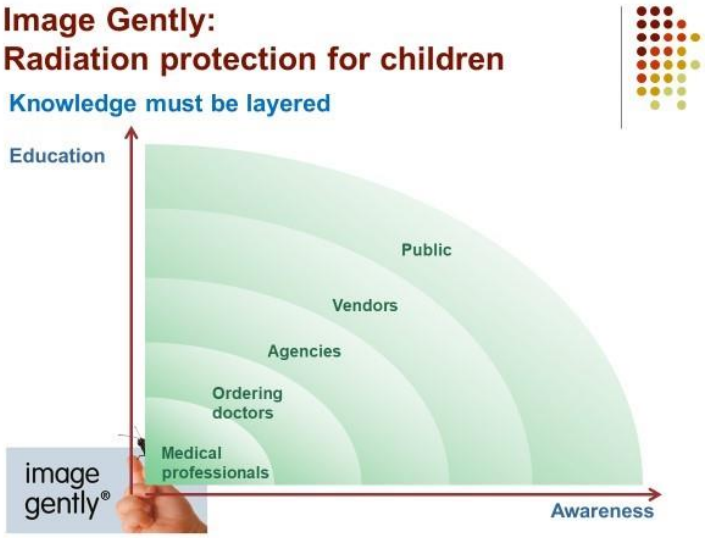

Fig. 5.1. An example of an expanded inclusiveness in optimisation education to all stakeholders. The Image Gently layered approach to RP for children: rethinking the approach to optimisation. (with permission from Image Gently).

(240) Less than 10% of healthcare resources are spent on children so that 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 under one 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 to 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, the ability of the patient to cooperate, and alternative examinations available locally to answer the clinical question.

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

(241) 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. The ICRP has provided guidance for diagnostic reference levels (DRLs) in ionising radiation imaging for children (ICRP, 2017) that is a starting point but not an end point for improvement opportunities (ICRP, 2022). For example, setting of a DRL should be followed by reaudit and continual reassessment to determine whether the facility can achieve the median reference value. 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 and outcomes include the patients, the workers, and the families and carers who often hold the children for the imaging to be successful.

5.1.1. Why "children are not small adults"

(242) On average, infants and children have a higher radiation sensitivity compared to adults. Many of their organs are more sensitive to radiation than those in adults, while other tissues have similar radiosensitivities (UNSCEAR, 2013). 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.

(243) 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 one, and by a factor of 100; yet 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.

(244) Yet, there are other reasons that children require more attention before, during, and after their imaging care (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 or who it was not possible to sedate. The pathology in children is different from that of adults so that the clinical protocols differ in basic ways; when children have cancers, these are large sarcomas that grow quickly, not carcinomas as seen in adults, and this enables CT 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 often 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 continued commitment to training in radiological protection to care for infants and children (Vassileva et al., 2022). Surveys by national and regional radiography organisations indicate inadequate paediatric training and wide variations in digital paediatric radiological practices (Morrison et al., 2011; McFadden et al., 2018; Alsleem et al., 2019; Foster et al., 2019).

(245) 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. Then, adopting a graded 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 continuously improved. 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.

(246) 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, the ICRP has recommended minimum 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

(247) 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 to care for children. The facility should provide a child-friendly environment that includes warm colours, decorations, furniture for children, with toys and distractions in the imaging rooms, and the provision of a childcare specialist if possible (Image Gently). These specialists may use a mock imaging room to introduce the child and family to equipment and a procedure beforehand (www.radiologyinfo.org). Online resources for the requesting 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 RP campaign websites. Some provide podcasts describing what to expect from their imaging procedures from a child's viewpoint.

(248) 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 healthcare. 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.

(249) 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/parents' language (via a translator). A recent study in the emergency setting revealed that less CT and radiographic imaging is undertaken if a translator is provided. 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 occur.

(250) Many imaging facilities have developed written decision aids or direct parents to web sites 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 (ICRPaedia; Image Gently; ACR-RSNA, 2020). In order to put risks into context an approximate value for the effective dose from a chest x-ray on a child is 0.1 mSv, equivalent to about 10 days exposure to natural background radiation (Image Gently, 2022a).

(251) To prevent unnecessary radiation exposures and repeat procedures, a time investment, on the one hand educating the referring physicians and on the other explaining to the child and family about the imaging procedures, are crucial. Additionally in the long run, 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

(252) An assessment is required for female adolescents (age 12–18 years) of the possibility of pregnancy prior to a procedure involving exposure of the abdomen. This group is particularly vulnerable to social and parental pressures that can potentially result in the patient providing misinformation about her 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 for this group. Staff may question adolescents separately from their parents and many facilities require a pregnancy test if there is any doubt about possible pregnancy, while in some countries imaging facilities may have policies that require all female 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; and angiography and interventions in the pelvic area under fluoroscopy. Additional procedures to consider include radiography of the abdomen, pelvis, hips, and lumbosacral spine (see for examples ACR-SPR, 2018).

5.1.4. Patient positioning and immobilisation

(253) Proper patient positioning is key to a successful imaging procedure and often overlooked when the infant or child is not cooperative. In these circumstances, measures should be taken to ensure the patient is immobilised during imaging. 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 is no longer considered appropriate (Section 2.3.4) and more efficient optimisation methods should be implemented.

(254) 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 exams; 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 should be provided for 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 (NICU). For more educational materials see Image Gently (2020e).

5.1.5. The importance of collimation in children

(255) Collimation matters more in limiting unnecessary radiation dose to infants and children than in adults. Collimation should be performed prior to radiation exposures. If a radiographer does not collimate a chest radiograph in a neonate (age< one month) 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 a fluoroscopy operator performs an upper gastro-intestinal procedure on a neonate and does not use adequate collimation, they will give unnecessary exposure 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 overranging (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).

(256) 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

(257) The acceptable level of image noise for answering a clinical question is often higher for paediatric imaging in facilities where images are interpreted by trained paediatric radiologists, as compared to adult imaging. 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 the 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.

(258) Use of a grid in radiography or fluoroscopy is usually unnecessary for infants and children under the age of 4 years (or <12 cm in AP diameter). In addition, parts of the body >12 cm with structure 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 longer exposure time are required if a grid is used. When high image resolution is necessary in interventional procedures, the use of copper filtration with a grid is useful. Grids should be modified

depending on patient size (2:1 to 6:1 for small size to at least 10:1 for chest radiographs and preferably 12:1) and for 100-130 cm source image distance SID (Image Gently, 2022a).

(259) The use of pulsed fluoroscopy, at the lowest rate tolerated by the operators at the facility, reduces the radiation dose significantly below the continuous fluoroscopy setting (Box 3.2). Experienced practitioners use 7.5 or lower 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.

(260) 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 5–7 weight categories for body CT imaging and 2-3 for head CT (ICRP, 2017; IAEA, 2020; AAPM, 2022).

5.2.1. Radiography

5.2.1.1. Choice of exposure factors and exposure levels

(261) In large surveys, 74–85% of all ionising radiation imaging procedures in children are radiographs (UNSCEAR 2000, 2008; Dorfman et al., 2011; NCRP, 2019). Digital radiographs use postprocessing to adjust for over and under exposures with 43% of paediatric radiographs being overexposed (Don, 2004). 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 exposure settings used are not higher than necessary. The Image Gently Campaign 'Back to Basics' approach can be used as a mnemonic to evaluate image quality. First, there are ten steps to understanding and applying the basics of the digital imaging environment in paediatrics.

(262) **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.

(263) **Understand the challenges associated with digital imaging**: DR is fundamentally different from film-screen, and exposure creep can lead to overexposures (see Section 2.2.3) (Gibson and Davidson, 2012). Moreover, vendor dependent image acquisition and terminology variation in processes has led to confusion in understanding image quality and techniques. Inadequate initial education and ongoing training in the radiology community about these issues in using DR have exacerbated problems with its use in children.

(264) **Learn exposure terminology standards**. Target Exposure Index (EI_T), Exposure Index (EI), and Deviation Index (DI) are discussed in Section 2.2.3. The DI indicates by how much the exposure for an imaging study deviates from the target value (see Table 2.2). Understand and pay attention to the kerma-area product (KAP) readings.

(265) **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 automatic exposure control (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, the AEC may be used on children if only the central sensor is activated and the child's body part is positioned to completely cover the entire single sensor. However, for infants and smaller children the imaged area of anatomy may be smaller than the single sensor and then manual techniques may be more appropriate. Focused exposure charts are important for key common exams such as chest, abdomen, and small parts.

(266) **Measure body part thickness**. 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-old (Kleinman et al., 2010). Therefore, patient age cannot reliably be used as a guide for techniques. Reverting "Back to Basics" by measuring patients with callipers will ensure that a standardised technique is selected. Knowing the body part and its thickness, one can then set the tube potential, filtration, and mAs for that specific study to "appropriately size" the examination for the child. Automated evaluation of patient thickness based on the exposure factors used and a knowledge of the characteristics of the x-ray detector might also be an option (Worrall et al., 2020). The goal is for reproducible, consistent images for children with body parts of similar sizes.

(267) **Use grids only when body thickness is >10–12cm**. 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 significantly degrade subject contrast in the image when the body part is over 10–12 cm of water-equivalent thickness. Structures that are greater than 12 cm thickness containing air, especially chest radiographs, can be successfully imaged without a grid. The use of grids should be minimised in children with less than 12–14 cm thickness (Carlton and Adler, 2013). Depending on the grid selected, anti-scatter grids double or triple the exposure factors necessary to obtain an adequate image.

(268) **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.

(269) The benefits of collimation prior to exposure are reduction in the area exposed, lowering the patient dose and KAP, and minimising scattered radiation, and so 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.

(270) **Additional filtration**: In the paediatric patient, total radiation must be kept low. This is the case with digital radiography or when high speed radiography systems are used. 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 incident air kerma 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.

(271) 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 aluminium plus 0.1 or 0.2 mm 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).

(272) **Display technique factors for each image.** The radiologist and radiographer should become familiar with technique factors used for common paediatric examinations. This requires that the tube potential, mAs, added beam filtration, EI, DI, and ideally KAP values 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.

(273) **Accept the noise level appropriate to the clinical question**. Radiologists prefer images that have little noise (Don, 2004; ACR–AAPM–SIIM–SPR, 2017), but noise intolerance can lead to exposure creep. To avoid this, radiologists need to become familiar with 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.

(274) 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.

(275) It is critical that radiologists, radiographers, and medical physicists (the core team) develop standards for their imaging facility through the **QA programme** (ICRP, 2022). An important element of this is **recording and monitoring exposure indicators** (Section 2.2.3, Table 2.2). In addition, regional and national DRLs are being developed for common imaging procedures, although provision of paediatric ones lag behind those for adults. The EU published PiDRLS in 2018 that includes paediatric abdomen, chest, skull, and pelvis radiography DRLs at several age or weight categories (ICRP, 2017; EU, 2018 Table 10.2a).

5.2.1.2. The Image Gently Back to Basics Tool for Evaluation of Image Quality

(276) 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 protection it provides from scatter is minimal (see Section 2.3.4; AAPM, 2019c; Hiles 2020, 2021). If the family requests shielding because it was used previously, the facility may use it with the family sharing in the decision making. When appropriate the last menstrual period should be documented to assess for pregnancy (see Section 5.1.3).
- **Immobilisation:** Could immobilisation help to reduce the chance of a repeat exposure? Should the facility seek immobilisation advice and training from a paediatric imaging

facility?

- **Indicators:** What does the EI mean and how can adjustments be made for similar patients undergoing the same exam? 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 properly demonstrated.

5.2.1.3. Imaging of neonates (up to 1 month) and infants (up to 1 year)

(277) In general, a small focal spot can be used in imaging the trunk for neonates and infants whereas a larger one is used for children and adults. A nominal focal spot value between 0.6 and 1.3 mm is usually suitable for paediatric patients. When a bifocal tube is used for radiography, the nominal focal spot value should be used, allowing for the most appropriate setting of exposure time and tube voltage at the chosen SID. This may not always be the smaller one (ICRP, 2013b).

(278) 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 5.2.1.2). Manual technique charts are often required for optimisation.

(279) Consider how an AP chest radiograph of a neonate, AP thickness 6 cm, compares to one of a large adult with a PA thickness of 30 cm. The half-value layer (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 DR detector might be performed with <60 kV and approximately 1 mAs.

(280) The Image Gently Campaign has a safety checklist for radiographers performing portable radiographs on children that can also be used for adults (see Box 2.4).

5.2.2. Fluoroscopic imaging

(281) While the use of fluoroscopy in adults has markedly decreased over the past decades with the increase in cross-sectional imaging and other endoscopic procedures, general gastrointestinal and genitourinary fluoroscopy continue to be routinely performed 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.

(282) Careful selection of equipment that provides safe and quality imaging for children is important. In the clinical practice of paediatric fluoroscopy, far fewer x-rays should be needed to create the images required for diagnosis compared to adult fluoroscopy, providing opportunities for reducing doses in infants and smaller children. Whereas the ESAK rate for an abdominal exam 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 0.45–0.59 mSv with continuous mode fluoroscopy might be only 0.05–0.07 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.

(283) 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 (GI) or genitourinary (GU) systems.

(284) A team approach to QA for dose management and image quality in paediatric fluoroscopy should be developed with the radiologist, radiographer, and medical physicist (ICRP, 2018a; Image Gently, 2020b). The development of paediatric DRLs will aid optimisation. Few have as yet been established for fluoroscopy, but the European Union PiDRLs include a DRL for micturating cystourethrogram (MCU) at 4 age levels (EU, 2018, Table 10.2a). An example of self assessment in dose management and quality improvement for MCU/VCUG paediatric fluoroscopy is available on the Society for Pediatrics Radiology web site (SPR, 2008).

(285) 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 from patients should be 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.

(286) 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 properly shielded? Are the hands holding the child out of the field of view? Is the patient positioned properly to start the fluoroscopy? The large relative size and noise of an image intensifier can be scary for young children so that cooperation can be a challenge. Preparation and teamwork are key.

5.2.2.1. Unique technical operator approaches

(287) 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, (the default setting is grid out where children are imaged primarily), copper filtration in addition to aluminium, use of the last image hold option, avoidance of magnification mode when possible, and the use of pulsed fluoroscopy on the lowest possible setting.

(288) Pulsed fluoroscopy settings should be the lowest possible that the operator is comfortable using (3.5–7.5 pulses per second), depending on the procedure being performed. The use of the last image hold feature allows not only time for the operator to review the image, to collimate or move the fluoroscopy image receptor, but it 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).

5.2.2.2. Suitable exposure factor programmes

(289) Assuming that aluminium filtration is used, the minimum tube potential should be 65 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, 2020b). 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, 2020b).

(290) There is no difference between children and adults for the focus to image receptor distance. During fluoroscopy, the patient should remain as far from the x-ray tube (at least 30 cm) and as close to the flat panel detector or image intensifier as is comfortable to reduce dose. High tube potential settings should be used to lower the dose.

(291) Patient dose should be recorded with all information made available from the fluoroscopic equipment (P_{KA}, $K_{a,r}$, see Annex A and fluoroscopy time). Although fluoroscopy time does not reflect the patient dose, it can be compared with that for other operators performing similar procedures in the review of operator technique.

(292) Fluoroscopic patient entrance dose rates are normally limited to the region 80–100 mGy min^{-1}, 88 mGy min^{-1} (10 R min^{-1}) in US and 100 mGy min^{-1} in Europe; however, when using cine mode, this is not true. Therefore, for safety reasons, it is suggested that cine mode be turned off when imaging infants and children unless required for interventional procedures.

(293) **Anti-scatter Grids:** Grids increase dose to the patient and may not be necessary for children with thicknesses less than 12 cm. When a grid is required, grid ratios of eight and line numbers of 40 lines/cm (moving grid) are usually sufficient even at higher radiographic voltage.

(294) **Automatic Dose Rate Control (ADRC)**: ADRC (or automatic brightness control) should be switched off during fluoroscopic examinations where there are relatively large areas with positive contrast medium (e.g. full bladders) to avoid excessive dose rates, (ICRP, 2013b).

(295) **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.

(296) **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 aluminium. Additional filters can further reduce the unproductive radiation and thus patient dose (ICRP, 2013b).

5.2.2.3. Portable fluoroscopy

(297) C-arm (portable) units for intra-operative use give higher doses to the patients and high scatter radiation to the operator; and are configured for adult patients. Mini C-arm units are FDA approved for orthopaedic fluoroscopy; but are unfortunately sometimes used for other applications. There are paediatric-focused C-arm units that should be considered for use at child-based facilities.

(298) 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 (SSD) 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).

5.2.3. Fluoroscopically guided interventions (FGIs)

(299) 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 carefully monitored. Intravascular iodinated contrast and gadolinium are relatively contraindicated in the neonate because of poor renal function, unless there is no alternative. Major paediatric interventional procedures should only be performed by experienced paediatric interventional radiologists due to their complexity.

(300) Optimisation and training for interventional procedures may include simulation with a doll or anthropomorphic phantoms and a pre-procedure checklist (Image Gently, 2020c). Radiation dose reduction can be considered in terms of the fluoroscopic pulse rate. In general, cardiac procedures use 30 pps where it is required to capture the rapid beat of the paediatric heart, while most other interventional procedures can use lower pulse rates to reduce the dose. Pulse rates of 3.5 (minimum) or 7.5 pps are recommended in paediatric fluoroscopy when possible (ICRP, 2013b; Image Gently, 2020b). Further, multi-modality imaging in the interventional imaging suite may allow use of ultrasound, especially in smaller children, and 2D tomography instead of CT.

5.2.4. Multi-detector CT procedures

(301) There are large variations in 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. Beyond the core team of radiographers, radiologists, and medical physicists or engineer, the larger team extends to include the CT equipment manufacturers (Fig. 5.1).

(302) 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 iterative and deep learning-based image reconstruction methods (Nagayama et al., 2021), photon counting CT, 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 head, chest, and abdomen CT in 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).

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

(304) 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. 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).

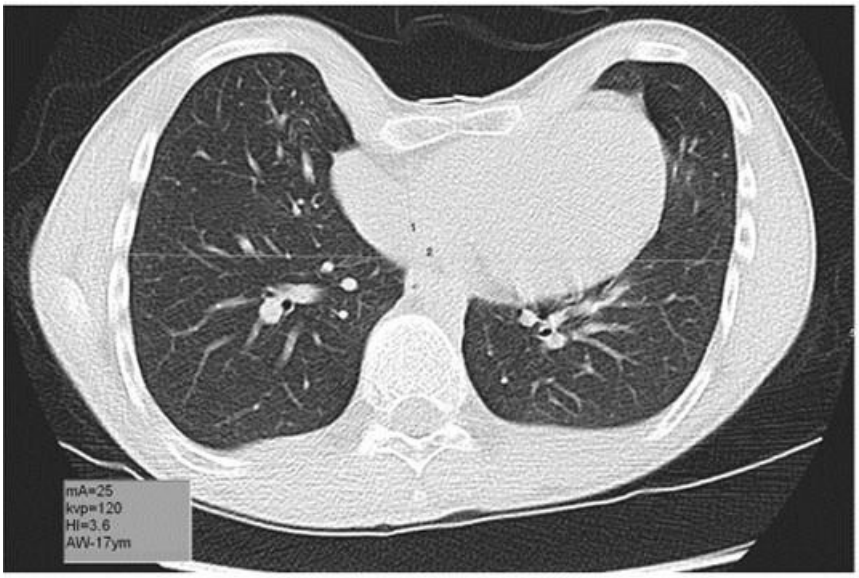

Fig. 5.3. Single image from a limited, low dose chest CT pre-surgery for Pectus Excavatum in a 17-year-old boy. The dose is low, but would be less with newer equipment and a lower tube potential. Technique: 120 kV, 12.5 mAs, rotation time 0.5 sec; dose indices $CTDI_{vol}$ 0.63 mGy, DLP 11.2 mGy cm. The measured Haller Index was 3.6 (severe). (K. Applegate, Dept of Radiology, University of Kentucky, retired)

(305) 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 ten step guide to optimisation for paediatric CT (Strauss K 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, 2020d) and important aspects to consider for the successful imaging of children are listed in Box 5.2.

Box 5.1. Questions to ask and statements to consider when planning a CT scan of a child

- Have you considered alternative imaging such as ultrasound or MRI?
- If a CT procedure is selected, child size the dose by choosing the tube potential and tube current appropriate for the size of the child (2-4 age categories are suggested for the head and 5-7 weight categories for the trunk) (ICRP, 2017).
- The 'scout', 'scanogram', or 'topogram' is an AP or PA (and sometimes lateral) image that is performed to select the start and stop points for the CT exam. The tube potential and mAs can often be lowered from the pre-set values.
- Use of contrast media: while iodinated contrast media are administered at room temperature in adults with no increased risk of extravasation, there is more use of contrast warmers in infants and young children to avoid the risk of temperature drop from contrast infusions.
- Scan only the indicated area of the body (do not over-range).
- Only scan once through the body part; pre- and post-contrast phase scans and delayed scans rarely add information but do increase radiation dose (Rostad et al., 2018).

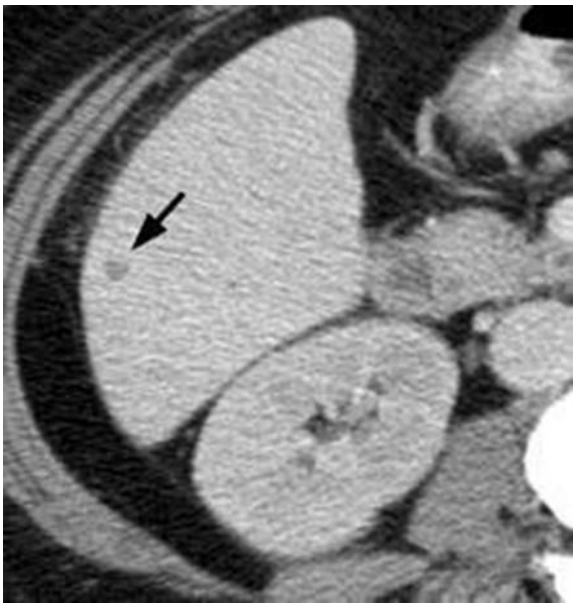

Fig.5.4 Example of an immunocompromised child with leukaemia and possible candidiasis. The protocol uses a mAs 20% higher than the standard to visualise a single low density lesion in the liver (arrow). (K. Applegate, Dept of Radiology, University of Kentucky, retired)

Box 5.2. Important aspects to consider for the successful imaging of children include:

- Preparing the patient and family (as noted above for fluoroscopy)
- Understanding why CT protocols differ from those for adults, it is not just about dose (see Section 5.1.2)
- Choice of exposure parameters
- Use of ATCM (automatic tube current modulation) with paediatric patients
- Challenges in use of automatic tube voltage selection in children (non-intuitive need to increase tube potential rather than decrease with some vendor software)
- Post-processing with iterative reconstruction and/or other techniques
- Dose audits of paediatric patients (ICRP, 2017, 2022)
- Methods for dealing with differences in patient size in dose audit to obtain usable data (a size specific dose estimate, SSDE (Box 4.1) (AAPM, 2011a, 2014)
- Use of software programmes that track dose and patient dose registries (Smith-Bindmann et al., 2019; ACR-DIR 2022)
- Reference to QA and dose management programme resources that are available for guidance (Strauss et al., 2010; ICRP, 2017, 2022; ACR DIR, 2022; Image Gently, 2020d)

(306) With the rapid acquisition time of CT imaging, it is uncommon to use sedation or anaesthesia in children or infants. Therefore, it is recommended that short acquisition times are used whenever possible, after checking that the number or projections does not compromise the quality of the clinical information. Exceptions include infants over 3 months (that cannot be swaddled) to age 4 years and that require intravenous contrast media; also, those paediatric patients who cannot be calmed through normal comforting by childcare specialists and/or distractors (see Section 5.1.2). There are also very thin collimation procedures such as temporal bone head CT that may require sedation/anaesthesia. Simulation with phantoms may be useful in making assessments.

(307) 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 level for the paediatric head age<2 years is 50 mGy and for age 2–5 years is 60 mGy; the notification value for the paediatric torso is 10 mGy for age <10 years using the 32 cm CT phantom.

5.3. Development of optimisation for paediatric imaging

(308) Optimisation of imaging for paediatric patients has additional challenges to those in adult radiology, because of the range in size, tissue composition and radiosensitivity with 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 (radiographer, medical physicist and radiologist), 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.

(309) 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, for referring physicians and staff, and family/carers.(ImageGently; ImageWisely; WHO, 2016; AAPM, 2022 (CT Protocols); IAEA, 2022; WFPI, 2022)

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 202b, 2020c).
- Standard pregnancy policy that includes verbal and written questions for adolescents, when pelvic imaging is performed.
- Paediatric DRLs should be developed.
- There is a standard review process to identify patients at higher risk, obtain written consent and plan beforehand all FGI procedures.
- 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 regularly reviewed by core team; and there is a process of continuous review of DRLs and achievable doses.
- 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.

3007

6. EXAMINATIONS OF PREGNANT PATIENTS

6.1. Introduction

(310) **Key messages 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 when emergency imaging is performed prior to pregnancy status being confirmed, and in these cases an accurate 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 female patients of childbearing potential should be questioned about pregnancy status before the performance of x-ray examinations in which the conceptus could be exposed - 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 considered to accomplish the clinical purpose with reduction in dose to both the conceptus and mother.**

(311) 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.

(312) Although trauma is the most common condition occurring in pregnant women, 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 magnetic resonance imaging (MRI)) are more frequently used 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

(313) Diagnostic and interventional x-ray examinations require that the radiologist 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, each specific instance should be justified'. 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.

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

(315) The situation is different if the conceptus is exposed primarily to radiation. When a diagnostic or interventional radiologic procedure is medically indicated, then 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 fluoroscopic IR procedures) may be involved, such as in cases of serious traumatic injuries of pregnant patients, resulting in conceptus doses greater than 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.

(316) The gestational period should also be taken into account during the justification process since 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 below 1 mSv, whereas the dose from the same type of examination may be higher than 10 mSv at 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

(317) 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.

(318) 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 an accurate conceptus dose estimate may be needed for patient counselling and reassurance. Fetal doses below 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

(319) Pregnant patients may be exposed either accidentally early in pregnancy or when emergency imaging is performed prior to pregnancy status being confirmed, and in these cases an accurate 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.

(320) Monte Carlo (MC) 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 anteroposterior (AP) and posteroanterior (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, choledocholithiasis 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).

(321) CT is an important imaging method not only for the general population but also for pregnant patients. When MRI is not immediately available, 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).

(322) 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

(323) 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 radiation exposure significance to the patient and family.

(324) 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 technologist/radiographer before the exam". A picture or illustration of pregnancy will clarify the message and gain more attention to the sign.

(325) All female patients of childbearing potential should be questioned about pregnancy status before x-ray examinations of the trunk are performed using a standardised form. 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 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.

(326) Adolescent girls 12–18 years old need also to be asked about their menstrual history and pregnancy status; however, they are particularly vulnerable to social and parental pressures and therefore, 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 fluoroscopically-guided interventional (FGI) procedures involving direct exposure of the abdominopelvic area as well as prior to PET/CT (ACR-SPR, 2018).

(327) The above are general guidelines regarding pregnancy screening before imaging potentially pregnant females. International and national guidelines are needed to address several issues associated with pregnancy assessment before radiologic examinations (Applegate, 2007). Establishing screening protocols using a multidisciplinary approach and taking into consideration local circumstances is essential to guide clinicians and radiologists and avoid accidental exposures.

6.5. Protective shielding of the conceptus

(328) 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 now no longer generally recommended. A position statement, the 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, and 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.

(329) 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 affect negatively the efficacy of the CT exam. It may elevate the x-ray 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

(330) Radiation risks to a conceptus associated with radiographs performed on the mother are negligible, unless these are repeatedly performed 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 determines that more are justified, then 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.

(331) It is well known that digital imaging for radiography has the potential for reducing patient radiation doses. The wide dynamic range of flat panel 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 radiology are discussed in Section 2 of this document and other information is available in the literature (IAEA, 2011).

(332) 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 μGy 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

(333) Pregnant women have unique physiology that leads to increased risks 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).

(334) 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.

(335) Iterative reconstruction (IR) of image data has been introduced for CT with the aim of reducing image noise. Advantage can be taken of IR to adjust exposure factors to lower the dose to the patient and conceptus dose while achieving a similar level of image quality to filtered back-projection reconstruction (Section 4.3). The use of IR is recommended for CT examinations of pregnant patients. 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.

(336) Several CT dose reduction tools have been developed during recent years for the modulation of tube current and x-ray tube potential. Automatic tube current modulation (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 considerably reduced when the ATCM tool is activated (Solomou et al., 2015). CT manufacturers have recently combined ATCM tools with automatic tube voltage selection algorithms that allow for automatic selection of x-ray tube potential and tube current settings. No published data exist on the effect of these systems on radiation dose and image quality in CT examinations performed on pregnant patients and, for this reason, this option should be used with great caution when imaging pregnant patients. To minimise radiation dose to superficial dose-sensitive organs such as the eyes, thyroid and breasts, 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 exams is not recommended.

(337) 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

(338) **CTPA for Pulmonary Embolism**: An example for suspected pulmonary embolism illustrates some of the issues and decisions to be made regarding the choice of imaging technique for pregnant patients. Multispecialty guidelines suggest avoidance of ionising radiation by using ultrasound of the lower extremity veins for evaluation of deep venous thrombosis (DVT). If positive, then treat accordingly. If uncertainty remains, then 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 (CTPA) delivers a higher dose to the breast and lung of the pregnant patient than lung perfusion scintigraphy, but it 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, CTPA is considered by many 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 CTPA 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 aortic arch to base of 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 from Image Wisely (2022b).

(339) **Computed tomography coronary angiography (CTCA)** 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 electrocardiogram. An effective radiation dose-saving technique in CTCA is prospective ECG-triggered scanning (see Section 4.5.2). When performing CTCA 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.

(340) **CT abdomen/pelvis:** Where this does affect the dose, use of pitch values less than 1.0 should be avoided in pregnant patients especially for abdominal and pelvic CT examinations. 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 CT examinations
• Avoid primary irradiation of the conceptus if at all possible • 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 about a quarter for chest scans and a half for scans of the upper abdomen (Hiles et al., 2020). • Avoid the use of pitch values less than 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 ATCM 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 at the gantry isocentre accurately

6.6.3. Optimisation in fluoroscopically-guided interventional (FGI) procedures

(341) 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, radiofrequency 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.

(342) 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 the extremities are associated with low conceptus dose (McCollough, 2007). For example, a typical catheter ablation procedure performed on young female patients requiring 0.58, 23, 5.3 and 10.2 minute exposures for groin-to-heart PA, PA, right anterior oblique, and left anterior oblique projections, respectively, is associated with a conceptus dose lower than 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 FGI 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.

(343) Dose management software systems are considered important tools for ensuring patient safety and image quality (ICRP, 2022). 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

(344) 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 report brings together practical aspects of optimisation of radiological protection for the various digital radiology modalities (radiography, fluoroscopy, and CT), which all require similar approaches, but with slightly different methods in their application.

(345) *Publication 15x* set out three building blocks on which strategies for achieving optimisation should be built (ICRP, 2022). The corner stone is collaboration between radiological professionals, with radiologists, radiographers and medical physicists working together as a team within an organisation that provides a structure for these processes. The radiologist 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. 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.

(346) This publication is aimed primarily at radiologists and other physicians, 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 and radiographers. There are also approaches for interventional procedures in Section 3, which will be of prime interest to the clinicians who perform them, but of relevance to other groups.

(347) 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 refined as more experience is gained.

(348) The 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.

(349) Vendors need to provide sufficient information and training about 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 are 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.

(350) 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 15x* for more detailed consideration of dose audit and image quality analysis (ICRP, 2022), and to *Publication 135* in relation to the use of DRLs (ICRP, 2017).

(351) 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.

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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 ICRU, (2005) on patient dosimetry is given based on the fundamental dose quantities defined in 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 (ESD)*	Radiography and fluoroscopy
Air kerma-area product	P_{KA}	mGy·cm^2 radiography Gy·cm^2 (fluoroscopy)	KAP	Dose-area product (DAP)*	Radiography, fluoroscopy, CBCT
Incident air kerma at the patient entrance reference point**	$K_{a,r}$	Gy	CAK (Cumulative air kerma)		Fluoroscopy and FGI procedures
Computed tomography air kerma index	C_K	mGy	CTDI, C_K	CT dose index (CTDI)*	Computed tomography
Volume CT air kerma index	C_{vol}	mGy	CTDI$_{vol}$, C$_{vol}$	Volume CT dose index (CTDI$_{vol}$)	Multi-detector computed tomography
Air kerma-length product	P_{KL}	mGy.cm	DLP, P$_{KL,CT}$	Dose-length product*	Computed tomography
Mean glandular dose**	D_G	mGy	MGD, AGD		Mammo-graphy

* Air kerma and dose in air are numerically equal in diagnostic radiology energy range.
**This quantity is not directly measured, but due to the standardised approach for its calculation, it is commonly displayed on equipment displays

A.1. References

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ANNEX B. AUTOMATED SYSTEMS FOR RADIATION EXPOSURE MONITORING

(B1) As discussed in ICRP (2022), 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). A brief explanation of some of the systems and standards used is given here.

B.1. Digital Imaging and Communication in Medicine (DICOM)

(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 a Radiation Dose Structured Report (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 (RDSR)

(B3) The RDSR is a DICOM information object that records data from radiation events in fluoroscopy, CT, mammography, CR and DR procedures in a standard format. A 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, 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 is general for all irradiation events, such as device serial number and performing physician, and also data that is specific for each irradiation event, such as tube voltage and beam angle. (Sechopoulos, 2015; Hellström, 2018). Modality specific parameters such as KAP, DLP, EI, and AGD (Annex A) are also recorded as required. The RDSR data is available on most CT scanners manufactured after 2012 (NEMA, 2013) and is available on the newest digital radiography and interventional systems. RDSR support on equipment used for interventional radiology was mandated by IEC in 2010 (IEC, 2010) 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, 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 RSDR 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, 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 covert 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 physicist needs to verify 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 (PACS)

(B8) A Picture Archiving and Communication System (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 transfer using DICOM format and other data stored in standard formats. A PACS has four major components: the 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 securely stored in off-site servers and accessed safely from sites in different locations via workstations or mobile devices.

B.4. Radiology information system (RIS)

(B9) A Radiology Information System (RIS) 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 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 RISs.

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 (2022) 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 PACS and RIS, and is being encouraged by the ACR (RSNA, 2020). More extensive and unified coding is evolving and the Radlex Playbook and 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 is aiming 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.

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ABBREVIATIONS

AAMC	American Association of Medical Colleges
AAPM	American Association of Physicists in Medicine
ABC	Automatic brightness control (see ADRC)
ACGME	Accreditation Council for Graduate Medical Education.(US)
ACR	American College of Radiology
ACR-SPR	ACR with Society of Paediatric Radiology
ACR-STR	ACR with Society of Thoracic Radiology
ADRC	Automatic dose rate control (also known as ABC)
AEC	Automatic exposure control
AFC	Alternative Forced Choice
AGD	Average Glandular Dose
AI	Artificial intelligence
ALARA	As low as reasonably achievable
AP	Antero-posterior
ATCM	Automatic tube current modulation
ATVS	Automatic voltage selection
BIR	British Institute of Radiology
BMD	Bone mineral density
CAK	Cumulative air kerma at patient entrance reference point
CBCT	Cone beam computed tomography
CoDE	Conceptus Dose Estimation
CR	Computed radiography
CNR	Contrast-to-noise ratio
COMARE	Committee On Medical Aspects od Radiation in the Environment (UK)
CT	Computed tomography
CTA	Computed tomography angiography
CTCA	Computed tomography coronary angiography
CTDI	Computed tomography dose index
$CTDI_{vol}$	Volume averaged CTDI
CTPA	CT pulmonary angiography
DAP	Dose-area product (see KAP)
DDR	Direct digital radiography (radiation sensitive diodes)
DI	Deviation index

DICOM	Digital Imaging and Communications in Medicine
DL	Deep Learning
DLIR	Deep Learning based Image Reconstruction
DLP	Dose Length Product
DMS	Dose management system
DR	Digital radiography - diode array storage
DRL	Diagnostic reference level
DSA	Digital subtraction angiography
DVT	Deep Venous Thrombosis
DECT	Dual Energy Computed Tomography
DXA	Dual x-ray absorptiometry
EC	European Commission
ECG	Electrocardiogram
EFOMP	European Federation of Medical Physics
EI	Exposure index
EI_T	Target exposure index
EMR	Electronic Medical Record (individual health information relating to imaging request)
ESAK	Entrance surface air kerma. (also $K_{a,e}$)
ESD	Entrance surface dose (see ESAK)
ESR	European Society of Radiology
ESTRO	European Society for Therapeutic Radiology and Oncology
EU	European Union
FBP	Filtered back projection
FDA	Food and Drug Administration (US Federal Agency)
FGI	Fluoroscopically guided intervention
FP	Flat panel
GI	Gastro-intestinal
GU	Genitourinary
HU	Hounsfield unit
HVL	Half-value layer
IAEA	International Atomic Energy Agency
IAK	Incident air kerma (at image receptor or patient entrance surface)
ICRU	International Commission on Radiation Units and Measurement
IDR	Indirect digital radiography (phosphor and diode)

IEC	International Electrotechnical Commission
IED	Integrated Energy Detector
II	Image intensifier
IOP	Institute of Physics (UK)
IPEM	Institute of Physics and Engineering in Medicine (UK)
IR	Iterative reconstruction
ISO	International Standards Organisation
KAP	Kerma-area product (also P_{KA}) (ICRP Glossary - Air-kerma, product)
KSC	Knowledge, skills and competences
kV	kilovoltage
LIH	Last image hold
LUT	Look up table
LOINC	Logical Observation Identifiers Names and Codes
mAs	Milliamp seconds (tube current x exposure time)
MC	Monte Carlo
MCU	Micturating cystourethrogram
MGD	Mean Glandular Dose
ML	Machine learning
MPR	Multi-planar reformats
MOSFET	Metal oxide semiconductor field effect transistor
MRI	Magnetic resonance imaging
NCRP	National Council on Radiation Protection and Measurement (US)
NEMA	National Electrical Manufacturers Association (US)
NICU	Neo-natal intensive care unit
PA	Postero-anterior
PACS	Picture archiving and communication system
PCCT	Photon counting CT
PiDRLs	Paediatric Diagnostic Reference Levels
PET	Positron emission tomography
PHE	Public Health England
PICC	Peripheral insert of central catheter
PMMA	Polymethyl methacrylate
pps	pulses per second
PSD	Peak skin dose

QA	Quality Assurance
QC	Quality Control
QMS	Quality Management System
RANZCR	Royal Australia and New Zealand College of Radiologists
RDSR	Radiation dose structured report
R/F	Radiography / Fluoroscopy
RIS	Radiology information system
RP	Radiological protection
RPOP	Radiation protection of patients (IAEA)
RSNA	Radiological Society of North America
SAFRAD	SAFety in RADiological procedures (IAEA)
SID	Source to image receptor distance
SIIM	Society for Imaging Informatics in Medicine
SNR	Signal to noise ratio
SPECT	Single photon emission tomography
SPR	Scan projection radiograph
SPR	Society for Paediatric Radiology (US)
SSD	Source to skin distance
SSDE	Size specific dose estimate
UNSCEAR	United Nations Scientific Committee on the Effects of Atomic Radiation
UQCM	User quality control manual
US	Ultrasound
VCUG	Voiding cystourethrography
VMI	Virtual Monoenergetic Images (CT)
WHO	World Health Organisation
WL	Window level
WW	Window width
2D, 3D, 4D	2-, 3- or 4- dimensional

GLOSSARY

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

Artificial intelligence (AI)

Artificial intelligence (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 there are sub-domains: machine learning (ML) and deep learning (DL) that are used to create decisions based on analysis of large-scale training data sets.

Automatic dose rate control (ADRC)

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 predetermined relationships.

Automatic tube current modulation (ATCM)

ATCM or automatic exposure control (AEC) determines the tube current level in CT 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.

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 only to the ‘contrast’ 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 contrast-to noise ratio may be similar or improved.

Deep learning (DL)

Deep learning is a subset of machine learning developed to learn from data without being explicitly programmed. 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 (DLIR) is being used for CT.

DICOM-Digital Imaging and Communications in Medicine

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. http://medical.nema.org/

Dose management system (DMS)

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 DRLs, checking compliance with DRLs, and provision of data at the time imaging is being performed to aid optimisation, especially for CT and interventional procedures. DMSs 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 DMSs.

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

CT 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 CT 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 CT 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)

Machine learning 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 explicitly programmed. 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.

Noise

Noise means the graininess of the image which is typically described by a single value representing the standard deviation (SD) of pixel values within a (homogeneous) region in the image. Noise can also be described by a noise-power-spectrum (NPS) 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, NPS is more comprehensive description of the noise compared to 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.

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 CT examination or pulsed fluoroscopy image series).

Radiology information system (RIS)

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 ICRPaedia Glossary) accumulated from a whole x-ray procedure expressed in Gy. The International Electrotechnical Commission (IEC 2010) 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 (ICRU) has not defined a symbol for this quantity. Ka,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 CT scanner by moving the couch through the CT gantry with the x-ray tube in a fixed position. Scan projection radiographs are performed at the start of a CT 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, surview, and scanogram.

Signal to noise ratio (SNR)

Signal-to-noise ratio (abbreviated 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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