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Radiological Protection in Paediatric Diagnostic and Interventional Radiology

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EDITORIAL

IMPROVING RADIOLOGICAL PROTECTION IN PAEDIATRIC MEDICINE

Ionising radiation has been used in medical applications for more than a century. There is no doubt that this has resulted in significant improvements in patient care due to enormous benefits in both diagnosis and therapy. In recent years, the advances in this field have been staggering, with the introduction of advanced imaging technologies and methods, highly specialised therapeutic uses of ionising radiation, and fluoroscopically guided procedures that allow surgical interventions unimaginable in decades past.

The International Commission on Radiological Protection (ICRP) continues to follow the rapid evolution of the use of radiation in medicine. The system of radiological protection encompasses all aspects, including protection of patients, comforters and carers, and volunteers in biomedical research, all of whom may receive medical exposures. Occupational exposures to physicians and other staff are also considered, as are public exposures that result from medical procedures. *Publication 105* (ICRP, 2007b) was prepared to describe, generally, how the system of protection in the Commission's 2007 Recommendations (ICRP, 2007d) applies to radiological protection in medicine, while several subsequent publications have dealt with this subject in more detail for specific medical applications.

As noted in the 2007 Recommendations (ICRP, 2007d), medical exposures are incurred within planned exposure situations. Dose limits do not apply because, in this case, the vast majority of the risks and benefits apply to a single individual, the patient. The case of comforters and carers, and volunteers in biomedical research is slightly more complex, but the same general principle applies. However, in all circumstances, including that of medical exposures, optimisation of protection is a key principle. To aid in optimisation in diagnostic procedures, ICRP has recommended the use of diagnostic reference levels. Broadening the use of reference levels to other medical exposures is under discussion.

In all circumstances, optimisation of protection is not about minimising dose, but rather balancing detriments and benefits. The same is true of medical exposures, where the Commission has been more explicit by saying that optimisation of protection of patients is about managing the patient dose commensurate with the medical

purpose. Reducing doses to reduce detriment to the patient is sensible but, for example, reducing computed tomography doses such that the image no longer gives the necessary diagnostic information, or therapeutic doses such that the procedure is not sufficiently efficacious, is contrary to good medical practice and not sound radiological protection.

Justification is also a key principle in medical exposures. *Publication 105* describes three levels of justification, one of which is justification of individual exposures. This is particularly important for high-dose examinations, such as complex diagnostic and interventional procedures. In this case, 'Individual justification by the practitioner is particularly important and should take account of all the available information. This includes the details of the proposed procedure and of alternative procedures, the characteristics of the individual patient, the expected dose to the patient, and the availability of information on previous or expected examinations or treatment' (ICRP, 2007b, Para. 67).

One of the important 'characteristics of the individual patient' is age. It is widely recognised that paediatric patients must be treated differently compared with their adult counterparts. In part, this is because infants and children have, on average, a higher risk of developing cancer than adults receiving the same dose. The longer life expectancy in children allows more time for any harmful effects of radiation to manifest, and developing organs and tissues are more sensitive to the effects of radiation.

The current publication covers some of the basic concepts of radiological protection in medicine, and specifically examines radiological protection for paediatric patients in diagnostic imaging, conventional radiography and fluoroscopy, interventional radiology, and computed tomography. Specific examples and guidance are provided. Annex A includes guidance for the appropriate use of paediatric radiological procedures by organ system for the central nervous system, neck and spine, musculoskeletal system, cardiothoracic system, gastrointestinal system, and genitourinary system.

Often, medical equipment and procedures are designed or set-up with the adult patient in mind, sometimes explicitly and sometimes not. In many cases where ionising radiation is used, adjusting the equipment or procedures for paediatric patients can result in significant improvements in radiological protection, delivering significantly lower doses for the same medical benefit. Although the current publication provides guidance on radiological protection specific to paediatric patients, the ultimate purpose is to improve radiological protection of children, a segment of the population for which we naturally want to take special care.

On a completely different note, the Commission wishes to welcome Michiya Sasaki to the ICRP Scientific Secretariat in Ottawa, Canada. Dr Sasaki joined ICRP in January 2012 as a cost-free expert. As ICRP Assistant Secretary, he assists the ICRP Scientific Secretary in many ways, including preparation for ICRP Main Commission meetings, development of the ICRP Annual Report, maintenance of the ICRP website, and notably publication of the *Annals of the ICRP*. He provided assistance on earlier publications, but starting with the last report, he is now recognised as Associate Editor of the *Annals of the ICRP*. Dr Sasaki would like to acknowledge the support of Mr Christopher Clement, Scientific Secretary, and Ms Lynn Lemaire,

Executive Assistant, which has made it possible for him to work comfortably and to 'get off on the right foot' in Ottawa. He would also like to thank members of his Japanese organisation, CRIEPI (Central Research Institute of Electric Power Industry), members of ICRP who have welcomed him into the ICRP 'family', and many other people who have kindly assisted with adjusting to work and life in Ottawa. Dr Sasaki looks forward to contributing to ICRP, and to enjoying a taste of the wonderful culture and beautiful nature that Canada has to offer.

Christopher H. Clement
ICRP Scientific Secretary
Editor-in-Chief

Michiya Sasaki
ICRP Assistant Secretary
Associate Editor

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Annals of the ICRP

Radiological Protection in Paediatric Diagnostic and Interventional Radiology

ICRP PUBLICATION 121

Approved by the Commission in October 2011

Abstract–Paediatric patients have a higher average risk of developing cancer compared with adults receiving the same dose. The longer life expectancy in children allows more time for any harmful effects of radiation to manifest, and developing organs and tissues are more sensitive to the effects of radiation. This publication aims to provide guiding principles of radiological protection for referring clinicians and clinical staff performing diagnostic imaging and interventional procedures for paediatric patients. It begins with a brief description of the basic concepts of radiological protection, followed by the general aspects of radiological protection, including principles of justification and optimisation. Guidelines and suggestions for radiological protection in specific modalities – radiography and fluoroscopy, interventional radiology, and computed tomography – are subsequently covered in depth. The report concludes with a summary and recommendations.

The importance of rigorous justification of radiological procedures is emphasised for every procedure involving ionising radiation, and the use of imaging modalities that are non-ionising should always be considered. The basic aim of optimisation of radiological protection is to adjust imaging parameters and institute protective measures such that the required image is obtained with the lowest possible dose of radiation, and that net benefit is maximised to maintain sufficient quality for diagnostic interpretation. Special consideration should be given to the availability of dose reduction measures when purchasing new imaging equipment for paediatric use. One of the unique aspects of paediatric imaging is with regards to the wide range in patient size (and weight), therefore requiring special attention to optimisation and modification of equipment, technique, and imaging parameters. Examples of good radiographic and fluoroscopic technique include attention to patient positioning, field size and adequate collimation, use of protective shielding, optimisation of exposure factors, use of pulsed fluoroscopy, limiting fluoroscopy time, etc. Major paediatric interventional procedures should be performed by experienced paediatric

interventional operators, and a second, specific level of training in radiological protection is desirable (in some countries, this is mandatory). For computed tomography, dose reduction should be optimised by the adjustment of scan parameters (such as mA, kVp, and pitch) according to patient weight or age, region scanned, and study indication (e.g. images with greater noise should be accepted if they are of sufficient diagnostic quality). Other strategies include restricting multiphase examination protocols, avoiding overlapping of scan regions, and only scanning the area in question. Up-to-date dose reduction technology such as tube current modulation, organ-based dose modulation, auto kV technology, and iterative reconstruction should be utilised when appropriate.

It is anticipated that this publication will assist institutions in encouraging the standardisation of procedures, and that it may help increase awareness and ultimately improve practices for the benefit of patients.

Keywords: Justification; Optimisation; Paediatric patient; Radiological protection; Diagnostic radiology; Interventional radiology

P-L. Khong, H. Ringertz, V. Donoghue, D. Frush,
M. Rehani, K. Appelgate, R. Sanchez

PREFACE

Committee 3 of the International Commission on Radiological Protection (ICRP) first began its work on optimisation of paediatric radiological protection in 2001 when it created the widely publicised 'CHILDSMART' slogan on a sticker and poster. This publication was first conceptualised in 2004 during the ICRP meeting in Beijing, where it was recognised that the subject of paediatric radiological protection was paramount in good radiological practice, and that such a document was necessary to promote the importance of the subject. It provides a comprehensive report on radiological protection in paediatric diagnostic and interventional radiology, with references made to prior ICRP publications prepared by Committee 3 on the practice of radiological protection in medicine, and aims to serve as guidance for referring clinicians and clinical staff who work with children in their practice. Moreover, there were requests from the professional community for ICRP to formulate recommendations in this area. Committee 3 proceeded in setting up a Working Party under the chairmanship of Hans Ringertz, comprising leading radiologists and medical physicist experts in the specialised field of paediatric radiology and radiological protection. Subsequently, in 2009, Pek-Lan Khong joined Hans Ringertz as Co-Chairman of the Working Party at the ICRP meeting in Porto.

The membership of the Working Party, who all made invaluable contributions to this publication, was as follows:

P-L. Khong (Co-Chair)	H. Ringertz (Co-Chair)	V. Donoghue
D. Frush	M. Rehani	K. Appelgate
R. Sanchez		

The report was further discussed and refined during internal discussions at the ICRP meetings in 2010 and 2011, and it greatly benefitted from comments obtained through the public consultation process. The Committee also wishes to acknowledge all contributions made by governmental as well as non-governmental organisations, and individuals who have kindly provided numerous helpful suggestions in the overall development of this publication.

EXECUTIVE SUMMARY

(a) This publication aims to provide guiding principles to protect paediatric patients from radiation for referring clinicians and clinical staff performing diagnostic imaging and interventional procedures, highlighting the specific issues which may be unique to the imaging of children.

(b) It begins with a brief description of the basic concepts of radiological protection, followed by the general aspects of radiological protection, including principles of justification and optimisation. Guidelines and suggestions for radiological protection in specific modalities – radiography and fluoroscopy, interventional radiology, and computed tomography (CT) – are subsequently covered in depth. The final chapter concludes with a summary and recommendations.

(c) The importance of rigorous justification of radiological procedures is emphasised for every procedure involving ionising radiation, especially with regards to modalities that impart a relatively high radiation dose: CT and interventional procedures. The use of alternative imaging modalities that are non-ionising should always be considered.

(d) The basic aim of optimisation of radiological protection for diagnostic imaging and interventional procedures is to adjust imaging parameters and institute protective measures in such a way that the required image is obtained with the lowest possible dose of radiation, and net benefit is maximised.

(e) The optimisation of radiological equipment for paediatric use with the broadest range of settings to address the wide range in patient size (and weight) is necessary. As most imaging equipment and vendor-specified protocols are structured for adults, modifications of equipment and exposure parameters may be necessary for paediatric use. The advice of medical physicists should be sought, if possible, to assist with installation, setting imaging protocols, and optimisation. Special consideration should be given to the availability of dose reduction measures when purchasing new imaging equipment.

(f) The development and regular updating of local, regional, or national diagnostic reference levels (DRLs) to assist in the optimisation process is encouraged. Also, regular audits of referral criteria, imaging quality, and imaging technique should be implemented as part of the radiological protection culture.

(g) Good radiographic technique requires attention to patient positioning and immobilisation, accurate field size and correct x-ray beam limitation, the use of protective shielding, and optimisation of radiographic exposure factors (e.g. focal spot size, filtration, antiscatter grid characteristics and appropriate use, focus to image plane distance, and tube current–exposure time product).

(h) Dose reduction techniques in fluoroscopy include the use of pulsed fluoroscopy, keeping the fluoroscopy table as far as possible from the x-ray source and the image intensifier as close to the patient as possible, limiting fluoroscopy time and restricting fluoroscopy to the evaluation of moving targets alone, the use of

virtual collimation for positioning prior to commencing fluoroscopy, tight collimation to the relevant anatomical area, and angling of the x-ray beam away from radiosensitive areas. Magnification should be kept to a minimum. Finally, radiation dose (air kerma–area product) should be recorded.

(i) Interventional procedures, particularly in small infants, should be performed by experienced interventional operators. All team members should undergo training in radiological protection, with a second, specific level of training required by some countries as this is a relatively high-dose procedure with the potential to impart high peak skin doses and absorbed doses to the exposed organs and tissues. The large size of the image intensifier relative to the size of the neonate, infant, or child, and the greater need for magnification compared with adults are factors that can potentially increase dose to the patient. Image acquisition runs should only be performed if necessary, and the fewest number of frames per second required to achieve the clinical objective should be used. Images should be obtained using tight collimation and the lowest magnification. Reduction of unnecessary dose, not only to the patient but also to the staff from exposure to scattered radiation, is important.

(j) For CT, dose reduction should be optimised by the adjustment of scan parameters (such as mAs, kVp, and pitch) according to patient weight or age, region scanned, and study indication (e.g. images with greater noise should be accepted if they are of sufficient diagnostic quality). Other strategies include restricting multiphase examination protocols, avoiding overlapping of scan regions, and only scanning the area in question. Attention should also be paid to minimising motion artefacts, meticulous use of intravenous contrast, and application of postprocessing techniques such as multiplanar and three-dimensional reconstruction as this can help improve study quality. Display monitors and the ambient environment should be optimised for the viewing of images. With regards to the use of local protective shielding, practices vary between institutions. Protocols should be tested specifically for each scanner as one approach is not appropriate for all scanners, and if not used properly, shielding may even increase radiation dose. If used, it is important to note that bismuth protection should only be placed after the scout view (or automatic exposure control prescanning) is performed, so that the system does not inappropriately increase tube current in the area of the shield. Shields should not be placed too close to the surface of the skin, and should be smoothly positioned over the surface to avoid artefacts. Finally, up-to-date dose reduction technology such as tube current modulation, organ-based dose modulation, auto kV technology, and iterative reconstruction should be used when appropriate.

1. INTRODUCTION

(1) Diagnostic radiological examinations in infants and children carry a higher risk, on average, for the development of cancer per unit of radiation dose compared with adults.

(2) The higher risk in children is explained by their longer life expectancy, which allows more time for any harmful effects of radiation to manifest; and the fact that developing organs and tissues are more sensitive to the effects of radiation. Moreover, the average risk is higher in infants and young children compared with older children (Preston et al., 2007).

(3) The increasing use of x-ray technology has resulted in a situation where the annual collective and per-capita doses of ionising radiation due to diagnostic radiology have exceeded those from the former largest source (natural background radiation) in several developed countries (UNSCEAR, 2008). Hence, it is imperative that all radiological examinations must be justified and optimised with regard to radiological protection in every patient, and this is especially important in paediatric patients.

(4) Computed tomography (CT) examinations may involve relatively high doses of radiation, and an estimated 7–10% of CT examinations are performed in children (Brenner and Hall, 2007; Berrington de Gonzalez et al., 2009). The absorbed doses to organs and tissues from paediatric CT are relatively high, and typically range from approximately 2 to 30 mGy to exposed organs.

(5) The objective of this publication is to provide guiding principles to protect paediatric patients from radiation for referring clinicians and clinical staff performing diagnostic imaging and interventional procedures, highlighting the specific issues that may be unique to the imaging of children.

2. BASIC CONCEPTS OF RADIOLOGICAL PROTECTION

2.1. Quantities and units

(6) The basic physical quantity used in radiological protection for stochastic effects (cell damage), such as cancer and heritable effects, is the absorbed dose averaged over an organ or tissue (i.e. mean absorbed dose; the energy deposited in the organ divided by the mass of that organ or tissue). For deterministic effects (tissue reactions resulting from cell killing), the absorbed dose is averaged over the highly irradiated portion of the tissue, such as the volume of irradiated skin in the direct radiation field. For further details on the definitions of stochastic and deterministic effects, please refer to Section 2.2. The SI unit for absorbed dose is joule per kilogram ($J\ kg^{-1}$) and its special name is gray (Gy).

(7) During medical imaging procedures using x-rays, mean absorbed doses in organs or tissues of the patient undergoing diagnostic or interventional procedures cannot usually be measured directly. However, significant progress has been achieved in recent years in providing methods to derive mean absorbed doses in organs and tissues from a number of practical measurements, and a considerable body of data is available (e.g. ICRU, 2005; IAEA, 2007). In practice, measurable quantities that characterise the external radiation field are used to assist in managing the patient dose. These include simple quantities such as entrance surface dose and entrance surface air kerma, and a number of other quantities of varying complexity depending on the nature of the x-ray equipment [e.g. for CT, see *Publications 87* and *102* (ICRP, 2000b, 2007a)]. For many years, dosimetric readings from these measurements have been expressed in terms of absorbed dose in air, such as entrance surface dose and dose area product, but the quantity that is actually measured with current dosimetric equipment is air kerma rather than absorbed dose in air. ICRU (2005) and IAEA (2007) recommend, therefore, the use of the field-related quantities in terms of air kerma, such as incident air kerma, entrance surface air kerma, and air kerma–area product for diagnostic reference levels (DRLs; see Section 3.2.3). Thus, the medical community should also be familiar with these quantities. Nevertheless, in this publication, quantities are expressed in dose in air in the data tables as they appear in the literature.

(8) Some types of radiation are more effective at inducing cell damage leading to stochastic effects. To allow for this, a quantity 'equivalent dose' (the mean absorbed dose in an organ or tissue multiplied by a dimensionless radiation weighting factor) has been introduced. This factor accounts for the type of radiation. For the principal type of radiation used in imaging (photons), the radiation weighting factor is 1, so the mean absorbed dose and the equivalent dose are numerically equal. The SI unit for equivalent dose is joule per kilogram ($J\ kg^{-1}$) and its special name is sievert (Sv). A detailed discussion on radiation weighting factors is provided in *Publications 92* and *103* (ICRP, 2003, 2007b).

(9) The same value for equivalent dose in different organs and tissues in the body results in different probabilities of harm and different severities. The Commission calls the combination of probability and severity of harm, 'detriment', meaning

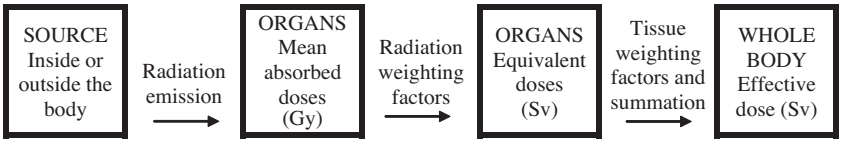

Fig. 2.1. The relationship between absorbed dose, equivalent dose, and effective dose.

health detriment. To reflect the combined detriment from stochastic effects due to the equivalent doses in all the organs and tissues of the body, the equivalent dose in each organ and tissue is multiplied by a tissue weighting factor, and the results are summed over the whole body to give the effective dose. The SI unit for effective dose is also joule per kilogram ($J\,kg^{-1}$) with the special name sievert (Sv). The tissue weighting factors are those recommended in *Publication 105* (ICRP, 2007b) and given in Table 2.1. The relationship between mean absorbed dose, equivalent dose, and effective dose is shown in Fig. 2.1.

(10) The Commission intended effective dose to be used as a principal protection quantity for the establishment of radiological protection guidance. It should not be used to assess risks of stochastic effects in retrospective situations for exposures in identified individuals, nor should it be used in epidemiological evaluations of human exposure because the Commission has made judgements on the relative severity of various components of the radiation risks in the derivation of detriment for the purpose of defining tissue weighting factors. Such risks for stochastic effects are dependent on age and sex, and risks for medical exposure are dependent on other factors such as health status. The age and sex distributions (and health status) of workers and the general population (for which the effective dose is derived) can be quite different from the overall age and sex distribution (and health status) for the population undergoing medical procedures using ionising radiation, and will also differ from one type of medical procedure to another depending on the prevalence of the individuals for the medical condition being evaluated. For these reasons, risk assessment for medical uses of ionising radiation is best evaluated using appropriate risk estimates, depending on mean absorbed dose or equivalent dose, for the individual tissues at risk, and for the age and sex distribution (and health status if known) of the individuals undergoing the medical procedures (ICRP, 2007b).

(11) Effective dose can be of practical value for comparing the relative doses related to stochastic effects from:

- different diagnostic examinations and interventional procedures;
- the use of similar technologies and procedures in different hospitals and countries; and
- the use of different technologies for the same medical examination

provided that the representative patients or patient populations for which the effective doses are compared are similar with regard to age and sex (and health status). However, comparisons of effective doses derived as given in Section 4.3.5 of the Commission's 2007 Recommendations (ICRP, 2007b) are inappropriate when there are significant dissimilarities between the age and sex distributions (and health

Table 2.1. Tissue weighting factors recommended in *Publication 103* (ICRP, 2007b).

	Tissue weighting factor (w_T)	Σw_T
Bone marrow (red), colon, lung, stomach, breast, remainder tissues*	0.12	0.72
Gonads	0.08	0.08
Bladder, oesophagus, liver, thyroid	0.04	0.16
Bone surface, brain, salivary glands, skin	0.01	0.04
	Total	1.00

* Remainder tissues: adrenals, extrathoracic region, gallbladder, heart, kidneys, lymphatic nodes, muscles, oral mucosa, pancreas, prostate, small intestine, spleen, thymus, and uterus/cervix.

status) of the representative patients or patient populations being compared (e.g. children, all females, elderly patients, seriously ill patients) and the Commission's reference distribution of both sexes and all ages. This is a consequence of the fact that the magnitudes of risk for stochastic effects are dependent on age and sex (and health status).

2.2. Summary of biological basis for radiological protection

(12) The biological effects of radiation can be grouped into two types: deterministic effects (tissue reactions) and stochastic effects (cancer and heritable effects). These effects are noted briefly here; the biological basis for radiological protection is covered in depth in the 2007 Recommendations (ICRP, 2007b).

2.2.1. Deterministic effects

(13) If the effect only results when many cells in an organ or tissue are killed, the effect will only be clinically observable if the radiation dose is above a threshold. The magnitude of this threshold will depend on the dose rate (i.e. dose per unit time) and linear energy transfer of the radiation, the organ or tissue irradiated, the volume of the irradiated part of the organ or tissue, and the clinical effect of interest. With increasing doses above the threshold, the probability of occurrence will rise steeply to l00% (i.e. every exposed person will show the effect), and the severity of the effect will increase with dose. The Commission calls these effects 'deterministic' (tissue reactions), and a detailed discussion and information on deterministic effects (tissue reactions) is found in ICRP (2007b). Such effects can occur in the application of ionising radiation in radiation therapy and interventional procedures, particularly when fluoroscopically guided interventional procedures are complex and require longer fluoroscopy times or acquisition of numerous images.

2.2.2. Stochastic effects

(14) There is good evidence from cellular and molecular biology that radiation damage to the DNA in a single cell can lead to a transformed cell that is still capable

of reproduction. Despite the body's defences, which are normally very effective, there is a small probability that this type of damage, promoted by the influence of other agents not necessarily associated with radiation, may lead to a malignant condition (somatic effect). As the probability is low at low doses, the occurrence of radiation-related cancer is accordingly low and may occur, at most, in only a few of those exposed. If the initial damage is to the germ cells in the gonads, heritable effects may occur. These effects, both somatic and heritable, are called 'stochastic'.

(15) The probability of a stochastic effect attributable to the radiation increases with dose and is probably proportional to dose at low doses. At higher doses and dose rates, the probability often increases with dose more markedly than simple proportion. At even higher doses, close to the thresholds of deterministic effects (tissue reactions), the probability increases more slowly, and may begin to decrease, because of the competing effect of cell killing. The probability of such effects is increased when ionising radiation is used in medical therapeutic or interventional procedures.

(16) Although a single radiological examination only leads to a small increase in the probability of cancer induction in a patient, in industrialised countries, each member of the population undergoes, on average, one such examination each year; therefore, the cumulative risk increases accordingly. Calculations performed on the assumption of a linear non-threshold model of radiation action estimate that the hypothetical proportion of cancer deaths in a general population that may be related to exposure from radiological procedures ranges from a fraction of one to a few percent of that cancer mortality (NAS/NRC, 2006). In addition, the risk is non-uniformly distributed in a population. Some groups of patients are examined much more frequently due to their health status. Also, some groups show higher than average sensitivity for cancer induction (e.g. embryo/fetus, infants, young children, those with genetic susceptibility). Moreover, cancers occurring early in life result in much higher lifetime loss than cancers that become manifest late in life. For the exposure of young children, the average risk would be higher, particularly for thyroid cancers (Preston et al., 2007). All these circumstances indicate that proper justification of radiation use and optimisation of radiation protection in medicine are indispensable principles of radiological protection.

(17) A detailed discussion and information on stochastic effects is found in ICRP (2007b), and the Commission's view on cancer risk at low doses is presented in *Publication 99* (ICRP, 2005). It is not feasible to determine on epidemiological grounds alone that there is, or is not, an increased risk of cancer following absorbed doses of the order of 100 mGy or below. The linear non-threshold model remains a prudent basis for the practical purposes of radiological protection at low doses and low dose rates.

3. GENERAL ASPECTS OF RADIOLOGICAL PROTECTION IN PAEDIATRIC DIAGNOSTIC IMAGING

3.1. Justification of diagnostic radiology procedures

(18) *Publication 103* (ICRP, 2007b) defined the general radiological protection principle that any examination requiring the use of ionising radiation requires that the referring healthcare provider, in consultation with the radiologist or authorised imaging healthcare practitioner, justify:

- that the use of the radiological examination in question will do more good than harm to the patient;
- that the specific radiological examination when required for a specific disease and age group has a specified objective, and this will usually improve the diagnosis or treatment, or will provide necessary information about the exposed individuals; and
- that the examination is required for that individual patient.

(19) It is very important for paediatric patients undergoing radiological examinations that the examination is indicated. A documented request for an examination including clinical information, signed or endorsed by a referring clinician, should be available before an examination is performed. If doubt arises, the final decision should be taken by the radiologist or authorised imaging healthcare practitioner in consultation with the referring clinician if necessary.

(20) The type of examination must be justified and every examination should result in a net benefit for the individual or for the public health. The examination should be anticipated to influence the efficacy of the decisions of the referring clinician with respect to diagnosis, patient management, treatment, and final outcome for the child (Dauer et al., 2008).

(21) Justification also implies that the necessary results cannot be achieved with other methods that would be associated with lower risk for the patient (European Commission, 1996).

(22) Justification requires that the selected imaging procedure is reliable (i.e. its results are reproducible and have sufficient sensitivity, specificity, accuracy, and predictive value with respect to the particular clinical question). Thus, the radiologist or authorised imaging healthcare practitioner responsible for the examination should have sufficient knowledge and experience to make an accurate interpretation of the examination. To make this possible, the examination should be performed by a qualified radiologist or by a radiographer/technologist in conjunction with appropriate monitoring for quality and safety measures by medical physicists. Justification also necessitates that a single person takes overall responsibility for the examination. This person, normally a radiologist, should be trained and experienced in radiological techniques and radiological protection as recognised by a competent authority. This person should work in close cooperation with the referring clinician in order to establish the most appropriate procedure for patient management and therapy. The

responsible person can delegate the task of performing the examination to a qualified technologist, who should also be suitably trained and experienced.

(23) The feasibility of alternative techniques that do not use ionising radiation, such as ultrasonography and magnetic resonance imaging (MRI), should always be considered. This is particularly true in paediatric patients with chronic diseases. Referral guidelines on imaging for clinicians are available from, for example, the American College of Radiology (1996) and the Royal College of Radiologists (2007). These guidelines discuss the appropriateness of the imaging modalities available to investigate many common clinical problems. Illustrative examples of such guidelines for paediatric patients from the Royal College of Radiologists are provided in Annex A.

(24) Before an x-ray examination, it is important to determine whether a female patient of childbearing age and potential is or may be pregnant. The last menstrual period should be documented. When a patient has been determined to be possibly pregnant, depending on patient reliability and history, the physician may want to order a pregnancy test if the fetus will be in the direct beam and/or if the procedure is of relatively high dose (ICRP, 2000a).

(25) All requests for biomedical research projects that involve the use of ionising radiation should be analysed individually. Institutions need to ensure that there are suitable mechanisms in place through the research and development procedures (e.g. the radiological protection committee in coordination with the ethics review board of the institution) to enable biomedical research exposures to be individually justified. There should be a high probability of establishing clear benefits to paediatric patients in the eventual outcome.

3.1.1. Examples of unjustified paediatric radiographic examinations

(26) The following are some examples of radiographic examinations that are not routinely justified:

- skull radiograph in an infant or child with epilepsy;
- skull radiograph in an infant or child with headaches;
- sinus radiograph in an infant or child under 6 years of age suspected of having sinusitis;
- cervical spine radiograph in an infant or child with torticollis without trauma;
- radiographs of the opposite side for comparison in limb injury;
- scaphoid radiographs in children under 6 years of age; and
- nasal bone radiographs in children under 3 years of age.

(27) The use of routine daily chest examination in intensive care units should be discouraged, and should only be performed for specific indications (Valk et al., 2001). These guidelines have been published by the American College of Radiology (1996).

(28) Radiological examinations requested purely for medicolegal purposes, such as bone-age request in immigrant adolescents, are not medically justified (ICRP, 2007b).

3.2. Optimisation of radiological protection

(29) The basic aim of the optimisation of radiological protective during an examination is to adjust imaging parameters and institute protective measures in such a way that the required image is obtained with the lowest possible radiation dose, and net benefit is maximised [i.e. the ALARA (as low as reasonably achievable) principle[1] should be adhered to for every examination].

(30) Optimisation of radiological protection involves three main aspects: radiological equipment, ensuring adequacy of radiological equipment and technical parameters such that they are adequately tailored to paediatric patients, and DRLs applicable to paediatric patients.

3.2.1. Radiological equipment

(31) As part of the optimisation process, it is important to ensure that equipment is working properly, delivering the appropriate exposures, and compliant with established standards of installation and performance. This starts with the procurement process, where equipment should be purchased so that its performance is to a level set out in a written specification that requires compliance with relevant international, national, or regional, as well as professional standards.

(32) Once installed, the equipment should be both acceptance tested and commissioned so that its performance to these standards is verified. In some countries, this should be done by an agent (physicist or engineer) other than the supplier who acts for the end user/hospital or the national regulatory agency. Whether or not it is legally required, advice of medical physicists should be sought, if possible, and it is important that it is followed and documented properly, even in the case of relatively simple equipment such as intra-oral dental systems. Proper documentation will make it easier to identify the omission of system components such as filters or units with pulsed fluoroscopy.

(33) After introduction into routine use, it is important to ensure that the equipment continues to perform satisfactorily. This can be assured by routine constancy checks, performed and documented regularly by the institution. Suggestions for appropriate tests and their frequency are available (IPEM, 2005). An example for a general radiography unit is to check if the x-ray beam is coincident with the light beam localisation system (Horwitz et al., 1993). Next in importance would be to measure the x-ray beam output and check for the presence of filters. Other relatively

[1] Sometimes the abbreviation 'ALARA' is used as equivalent to the term 'optimisation of protection' or in replacement thereof. However, it should be kept in mind that the expression 'as low as reasonably achievable' is only part of the concept of optimisation. The entire concept implies, more precisely, keeping patient exposure to the minimum necessary to achieve the required medical objective (diagnostic or therapeutic). In diagnostic imaging and x-ray-guided interventions, it means that the number and quality of images are sufficient to obtain the information needed for diagnosis or intervention. In radiation therapy, ALARA only applies to normal tissue, as the dose to the target is not expected to be as low as reasonably achievable, but rather, the opposite. Use of the abbreviation 'ALARA' alone and out of this context may be misleading and raise unnecessary controversy.

easy quality control tests are often provided by the manufacturers with equipment such as CT scanners. At a more demanding level, it is important to review the performance of each machine comprehensively at appropriate intervals (IPEM, 2005), or after the machine undergoes a major repair or service (e.g. a tube change). All of these quality control procedures should be documented properly. Finally, it is essential that this process of assessing equipment performance is integrated into the management of the department, so that the findings of tests are noted and acted on.

3.2.2. Adequacy of equipment and technical parameters

(34) As most imaging equipment is structured to handle adult patients, modifications of the abovementioned parameters and the hardware may be necessary both at installation and later in the use of the equipment. Ideally, equipment specifically designed for paediatric patients should be installed, especially in facilities with a large workload of paediatric patients. X-ray equipment used for paediatric procedures should have the broadest range of settings to optimise protection to the size of the child. Protocols that cover a selection of the technical parameters tailored for common types of x-ray examinations should be pre-installed.

(35) Special consideration should be given to dose reduction measures when purchasing new radiographic or fluoroscopic equipment for paediatric use (e.g. virtual collimation, low-attenuation table tops, removable grids, the availability of pulsed fluoroscopy, last-image hold and capture, spectral filters and adaptive technologies to minimise blooming, etc.). Adding a copper filter in addition to the aluminium filtration should be considered if not provided. For standard tube voltages, each 0.1 mm of copper is equivalent to approximately 3 mm of aluminium.

3.2.3. Diagnostic reference levels in paediatric radiology

(36) To assist in the optimisation process of medical exposure to patients, the concept of DRLs has been introduced. A DRL value is advisory, and in practice is set so that if the value is exceeded regularly, the practice involved should be investigated. This does not mean that there is necessarily unacceptable practice; rather, the practice requires explanation, review, or possibly a new approach. The radiological protection principle of dose limits used for exposure of workers and the general public does not apply to medical exposures for patients.

(37) In practice, a field-related quantity that is easy to measure is utilised to implement the concept of DRLs (e.g. entrance surface dose and entrance surface air kerma, etc.).

(38) ICRP does not specify quantities, numerical values, or details of implementation for DRLs. This is the task of the regional, national, and local authorised bodies, each of which should meet the needs in their respective areas. An example is the European Union DRLs for 5 year olds in paediatric radiology (European Commission, 1996, 1999). These values were established by surveying an appropriate field-related quantity for a number of common projections in more than 100

paediatric hospitals (Schneider et al., 1992, 1998; Perlmutter et al., 1998). For general radiography, various projections of chest, skull, abdomen, spine, and pelvis are surveyed. The upper DRL is often taken as the third quartile value (i.e. the value below which the measurements for three-quarters of the institutions lie); a lower DRL may also be selected. Thus, there is reasonable expectation that measurements taken in any institution should lie below the upper DRL, and if above, it should be possible to reduce exposures below the DRL without loss of clinical information. For example, excessive use of an antiscatter grid may result in entrance surface dose values above the upper DRL. With review of technique, image quality, further education, and training, the resultant entrance surface dose values will potentially be below the upper DRL. It is important to understand that it is possible that the entrance surface dose values may be too low, and corrective action in this regard may also be warranted when the value is consistently below a selected lower DRL.

(39) DRLs for some conventional radiographic examinations are given in Table 3.1. It is important to be aware that these are for 5 year olds and that different values would be obtained with other age groups, such as infants or 10 year olds. Some available data for these older and younger age groups are presented in Table 3.2, but these have not been adopted as DRLs to date (European Commission, 1996). Formally adopted European Union DRLs have been limited to the 5-year-old group on the grounds that assessing results for even one group will give a marker for department performance. It is important to note that these DRLs were obtained prior to the widespread introduction of computed radiography (CR) and digital radiography (DR) in many parts of the world, and they need to be extended and re-evaluated (ICRP, 2004) to take account of recent developments. A study evaluating adult patient entrance surface doses for CR after transition from conventional

Table 3.1. Examples of diagnostic reference levels in paediatrics for standard 5-year-old patients, expressed in entrance surface dose per image for single views (European Commission, 1996).

Radiograph	5-year-old patients Entrance surface dose per single view (mGy)*
Chest: postero-anterior	0.1
Chest: anteroposterior (for uncooperative patients)	0.1
Chest: lateral	0.2
Skull: postero-anterior/anteroposterior	1.5
Skull: lateral	1.0
Pelvis: antero-posterior	0.9
Abdomen: anteroposterior/postero-anterior with vertical/horizontal beam	1.0

* Upper diagnostic reference level expressed as entrance surface dose to the patient. The entrance surface dose for standard-sized patients is the absorbed dose in air (see explanation in Para. 7 on the use of air kerma vs absorbed dose to air) (mGy) at the point of intersection of the beam axis with the surface of a paediatric patient, backscatter radiation included.

Table 3.2. Variations of entrance surface dose* (converted to mGy, to the nearest two decimal places) observed in the three European Union paediatric trials (1989/91, 1992, 1994/95): median, minimum–maximum values and corresponding ratio (minimum:maximum) of frequent x-ray examinations in paediatric patients.

Examination type	Infant			5 year old			10 year old		
	Median	Min–max	Min:max	Median	Min–max	Min:max	Median	Min–max	Min:max
Chest AP (1000 g newborn)	0.05	0.01–0.34	1:35						
Chest PA/AP	0.08	0.02–1.0	1:47	0.07	0.02–1.35	1:71	0.07	0.02–1.16	1:68
Chest AP (mobile)	0.09	0.03–0.72	1:21	0.07	0.03–0.33	1:11	0.09	0.03–0.76	1:26
Chest lateral				0.14	0.04–0.55	1:15	0.15	0.04–1.98	1:51
Skull PA/AP	0.93	0.15–4.51	1:30	1.00	0.24–4.63	1:19	1.04	0.13–5.21	1:40
Skull lateral				0.70	0.14–2.36	1:17	0.58	0.11–3.79	1:33
Pelvis AP	0.26	0.02–1.37	1:76	0.49	0.09–2.79	1:32	0.81	0.09–4.17	1:47
Full spine PA/AP	0.87	0.12–0.44	1:41						
Thoracic spine AP							0.89	0.20–4.31	1:21
Thoracic spine lateral							1.63	0.30–6.66	1:22
Lumbar spine AP							1.15	0.13–5.69	1:43
Lumbar spine lateral							2.43	0.25–23.5	1:94
Abdomen AP/PA	0.44	0.08–3.21	1:42	0.59	0.06–2.92	1:52	0.73	0.15–3.98	1:27

AP, anteroposterior; PA, postero-anterior.

* See definition for entrance surface dose in Table 3.1.

Table 3.3. Examples of UK national reference doses for fluoroscopy examinations on paediatric patients – 2005 review from the National Patient Dose Database, UK.

Examination type	Standard age (years)	Dose area product per examination (Gy cm^2)
Micturating cystourethrogram	0	0.3
	1	0.7 (0.8)
	5	0.8 (0.8)
	10	1.5
	15	2.5
Barium meal	0	0.4
	1	1.1 (1.2)
	5	1.3 (1.2)
	10	2.4
	15	6.4
Barium swallow	0	0.4
	1	1.2 (1.3)
	5	1.3 (1.3)
	10	2.9
	15	3.5

radiographic examinations found that dose reduction was between 15% and 38% of the European Union DRLs established for screen-film radiography, and between 28% and 41% of the reference values recommended by the American Association of Physicists in Medicine (Vañó et al., 2007). Some data for UK values for fluoroscopic studies have been determined (Hart et al., 2007) and compared with equivalent DRLs documented in Great Ormond Street Hospital, London (Hiorns et al., 2006). Table 3.3 shows recommended reference doses in the UK derived from the National Patient Dose Database for micturating cystourethrograms, barium meals, and barium swallows (Hart et al., 2007). For neonatal anteroposterior chest radiographs, DRLs for entrance surface doses of 80 μGy and 50 μGy have been proposed by the European Commission (1996) and the National Radiological Protection Board (Hart et al., 2000), respectively.

3.3. Quality criteria implementation and audit

(40) As part of the radiological protection culture, there is a need for follow-up and regular audits after implementation of quality criteria (Schneider et al., 1993; Schneider, 1995).

(41) Audits of referral criteria, image quality, and imaging technique in paediatric radiology practices have found that better results are obtained for paediatric specialist centres compared with non-specialist centres (Cook et al., 2001; Alt et al., 2006). Thus, sharing of good practice by paediatric specialist centres is important for improving practices and patient outcomes.

(42) The following are some examples of auditing procedures implemented for radiological protection in paediatric practices and the favourable outcomes that were achieved:

- For paediatric skull trauma, an audit of the recommended guidelines for CT examinations demonstrated that adjustments in clinical referring practices resulted in an eight-fold decrease in CT utilisation (Macgregor and McKie, 2005). In the same way, repeated audits resulted in marked reduction in skull radiographs and significant improvement in compliance with guidelines for paediatric head trauma (Johnson et al., 2004).
- For the use of gonad shielding, audit of correct placement after dose reduction measures were introduced improved the outcome of shielding. The percentage of correct placement was increased from 32% and 22% to 78% and 94% for boys and girls, respectively (McCarty et al., 2001).

4. RADIOLOGICAL PROTECTION IN CONVENTIONAL PAEDIATRIC RADIOGRAPHY AND FLUOROSCOPY

(43) For every radiographic examination, there is a need to specify criteria for anatomical coverage and radiation dose to the patient, and examples of good radiographic technique by which the diagnostic requirements and dose criteria can be achieved.

4.1. Patient positioning and immobilisation

(44) Patient positioning has to be exact even if the patient does not cooperate so that the beam can be correctly centred, the proper projection and collimation can be obtained, and non-examined parts of the body can be shielded.

(45) Immobilisation is required in many infants and young children when performing radiographic studies. Devices, such as foam rubber devices, may be used in very small infants. It may be useful to take advantage of the period when the infant is calm or asleep after a feed to perform the radiological examination. Immobilisation devices should be easy to use and their application should not be traumatic to the patient (or caregivers). Their use and benefits should be explained to the accompanying caregiver.

(46) The paediatric patient should only be held by radiological staff[2] in exceptional circumstances. When hospital personnel help to immobilise a child, this is regarded as an occupational exposure and care should be taken to ensure that the staff are not repeatedly exposed to radiation. When physical restraint by parents or other accompanying persons is unavoidable, they should be informed about the exact procedure and what is required of them, in particular the effect of distance from the primary beam. They should be provided with a protective apron and remain outside the primary beam of radiation. The caregiver's hands, holding the child, should not be exposed to the radiation beam, and protective gloves may be provided to protect from exposure to scattered radiation.

(47) The time allocation for an examination should include time to explain the procedure not only to the accompanying caregiver, but sometimes also to the child. Time is well spent in achieving an optimised examination fulfilling the necessary quality criteria (European Commission, 1996). This procedure can be simplified by providing information explaining the details of the procedure to be undertaken in advance of the study. The provision of videos, written material, or websites specifically designed for children and parents in the waiting area or in the examination room prior to the studies can be helpful.

[2] The term 'worker' is defined by the Commission in *Publication 103* (ICRP, 2007b) as 'any person who is employed, whether full time, part time or temporarily, by an employer, and who has recognised rights and duties in relation to occupational radiological protection'. In a hospital, these persons are part of the staff. The term 'staff' is preferred in this report because the intended audience is more familiar with this term.

4.2. Field size and x-ray beam limitation

(48) A field that is too large will result in unnecessary radiation dose outside the area of interest, and impair the image contrast and resolution by increasing the scattered radiation. This lack of collimation is a potential pitfall, especially in CR/DR where postprocessing techniques may be used to crop the image after image acquisition. Although a certain degree of flexibility may be necessary to ensure that the entire field of interest is included, repeated use of unnecessarily large field sizes in paediatric patients is inappropriate. On the other hand, a field that is too small increases the risk of a diagnostic error or may require a second exposure.

(49) Correct beam limitation requires knowledge of external anatomical landmarks. These landmarks change with the age of the patient due to varying proportions of the body during development. The size of the field of interest is also dependent on the underlying disease. Thus, basic knowledge of paediatric anatomy and age-specific disorders is required of the radiographer/technologists to ensure proper beam limitation in all age groups. It is important to use collimation to expose only the area intended for examination, rather than, for example, doing 'babygrams' (whole body, chest, abdomen, and pelvis on one image) in neonates.

4.3. Protective shielding

(50) Good radiographic technique includes standard use of lead or equivalent shielding of the child's body in the immediate proximity of the diagnostic field. The use of additional shielding should also be considered for certain examinations to protect against external scattered and extrafocal radiation.

(51) When the breasts, gonads, and/or thyroid lie within 5 cm of the primary beam, they should be protected whenever this is possible without impairing the necessary diagnostic information. For exposures of 60–80 kV, a maximum gonadal dose reduction of approximately 30–40% can be obtained by shielding with 0.25 mm of lead-equivalent material immediately at the field edge. However, this is only true when the protection is placed correctly at the field edge. If poorly placed, such shielding may worsen image quality, and in some cases, shielding may not be appropriate (Dauer et al., 2007) (see Section 6.6 on protective shielding for CT scans). Doses to tissues outside the x-ray beam occurring from internal scatter radiation cannot be shielded.

(52) Non-lead protective devices are available and may be more environmentally friendly and more durable. The lead equivalent of non-lead protective clothing depends on the radiation quality (i.e. tube voltage and filtration). Therefore, the protective efficacy may not be reflected by a single value, but instead, the energy-dependent attenuation, which is measured in a broad beam geometry accounting for scattered radiation, characterises the radiation protection much more precisely (Eder et al., 2005).

(53) There is typically no reason to include the male gonads within the primary radiation field for radiographs of the abdomen. The same is usually valid for examinations of the pelvis and micturating cystourethrograms. The testes should

be protected by securing them within the scrotum to avoid upward movement caused by the cremasteric reflex. The testes should be protected with a protective capsule but kept outside the direct radiation field. Lead or equivalent shields for girls and lead or equivalent capsules for boys are commercially available or may be made in-house. They should be available in many sizes. Using properly adjusted capsules, the absorbed dose in the testes can be reduced by up to 95%.

(54) In girls, shadow masks within the diaphragm of the collimator are as efficient as direct shields. They can be positioned more exactly and do not slip as easily as contact shields. When shielding of the female gonads is appropriate, the reduction of the absorbed dose using effective shielding for the ovaries can be approximately 50% (Fawcett and Barter, 2009). In abdominal or pelvic examinations for girls, gonad protection may not be possible [e.g. for the indications of trauma, incontinence, and abdominal pain, misplaced shielding may mask important pathology (Bardo et al., 2009)].

(55) Postero-anterior projection in radiography of the skull rather than anteroposterior projection can reduce the absorbed dose in the eyes. Therefore, postero-anterior projection is preferred as soon as the patient is old enough to cooperate, such that prone or erect positioning is feasible.

(56) In girls of pubertal age, the developing breast tissue is particularly sensitive to radiation, and thus exposure should be limited as much as possible (e.g. using postero-anterior projection rather than anteroposterior projection in chest and spine x-rays).

(57) Shielding of thyroid tissue during dental x-ray examinations has been shown to have little effect on dose reduction provided that the distance to the primary field is kept at more than 2 cm.

4.4. Radiographic exposure conditions

(58) Knowledge and correct use of appropriate radiographic exposure factors [e.g. focal spot size, filtration, focus to image plane distance, and the tube current–exposure time product (tube voltage, mAs product)] is necessary because they have a considerable impact on image quality, and this may have implications for patient radiation exposure. Permanent parameters of equipment such as inherent tube filtration and antiscatter grid characteristics should also be taken into consideration.

4.4.1. Nominal focal spot size

(59) One should endeavour to achieve good image detail by maintaining a balance between the use of a small focal spot size and a short exposure time. Usually, a nominal focal spot value between 0.6 and 1.3 is suitable for paediatric patients (e.g. IEC62220-1 requires a focal spot value of 1.2). When bifocal tubes are available, the nominal focal spot value should be that which allows for the most appropriate setting of exposure time and tube voltage at a chosen focus to image plane distance, and this may not necessarily be the smaller option.

4.4.2. Additional filtration

(60) The x-ray spectrum includes photons of different energies. The low-energy photons (i.e. the soft part of the spectrum) are completely absorbed in the patient's skin and do not contribute to image generation, unnecessarily increasing the patient dose. Most tubes have a minimum filtration of 2.5 mm of aluminium, which includes inherent filtration plus fixed filters. Additional filters can further reduce the non-productive radiation and thus patient dose, with the exception of use in neonates and very small infants as the tube potentials used are relatively low.

(61) Rare earth filter materials with absorption edges at specific wavelengths have little or no advantage over simple inexpensive aluminium–copper (or aluminium–iron) filters, which can easily be made in-house provided that the appropriate high-purity material is available. All tubes used for paediatric patients in stationary, mobile, or fluoroscopic equipment should have the capacity to add additional filtration, and to be changed easily when appropriate. Generally, up to 1 mm aluminium plus 0.1 (or 0.2) mm copper is adequate as additional filtration.

4.4.3. Antiscatter grids

(62) Antiscatter grids increase contrast but also increase radiation dose to the patient. Thus, excessive patient dose may be avoided by not applying grids. In infants and young children, the use of antiscatter grids or other antiscatter measures is often unnecessary because of the relatively low scatter radiation produced in the irradiated volume (mass). With optimisation, grids are only necessary for older children, usually not younger than 8 years of age (Schneider et al., 2000).

(63) Grids incorporating low-attenuation materials such as carbon fibre or other non-metallic materials are preferable. Moving grids may present problems in very short exposure times (<10 ms). In these cases, stationary grids with high strip densities (density > 60 cm^{-1}) should be used. The accurate alignment of grid, patient, and x-ray beam, as well as careful attention to the correct focus-to-grid distance, is of particular importance. All these factors should be taken into consideration when performing quality control of the moving grid devices used for paediatric patients.

(64) Depending on the manufacturer's recommendations, fluoroscopic equipment with the capability for quick and easy removal of the grid should be used in paediatric patients. Removable grids are desirable not only for fluoroscopic units, but ideally for all equipment used for paediatric patients.

4.4.4. Focus to image plane distance

(65) Correct adjustment of the focus to image plane distance should always be observed when using a non-grid cassette technique. For overcouch tubes with grid tables, the focus to image plane distance is usually approximately 115 cm, and for vertical stands, approximately 150 cm. When no grid is used and the cassette is placed on the table, a focus to image plane distance of approximately 100 cm should

be chosen, ensuring that the same tube to table distance is obtained as with the grid. Special circumstances may require a longer focus to image plane distance.

(66) For all fluoroscopic examinations, patient to image plane and patient to image intensifier distances should be kept as short as possible to reduce patient dose.

4.4.5. Automatic exposure control

(67) Variation in size is large in paediatric patients compared with adults, as it may range from premature infants, weighing considerably less than 1 kg, to adolescents weighing in excess of 70 kg. Radiographers/technologists should be aware of this wide range in size, and thus the need to optimise automatic exposure control (AEC) devices for handling paediatric patients accordingly. Preferably, radiographers/technologists who are specially trained in paediatric radiography should operate the equipment.

(68) The optimal adaptation of radiographic technique to various clinical needs requires the use of digital plates or screen-film systems of different speeds and different switch-off doses at the image receptor. Screens and AEC chambers are energy dependent, particularly in the lower range of radiographic voltage, but the voltage required for screens and AEC chambers may not be the same, resulting in AEC devices lengthening the minimal exposure times. All these factors should be considered when AEC devices are used with paediatric patients.

(69) Specially designed paediatric AEC devices have a small mobile detector for use behind a lead-free cassette. Its position can be selected with respect to the most important region of interest. This should be done very carefully as even minor patient movements may affect image quality and patient dose. The high speed of digital plates requires a minute dose at the cassette front. Consequently, the detector behind the cassette has to work in the range of 1–10 μGy and this may be challenging to implement.

(70) With small children, exposure charts corresponding to radiographic techniques which take into account the patient's weight when examining the trunk, or patient size when examining the extremities, are much safer than AEC devices, easy to use and less expensive. These radiographic techniques can indicate when AEC devices may be used and which chamber should be selected.

4.4.6. Automatic brightness control in fluoroscopy

(71) Automatic brightness control should be switched off during fluoroscopic examinations where there are relatively large areas with positive contrast material to avoid excessive dose rates (e.g. contrast-filled full bladders).

4.4.7. Exposure time

(72) In paediatric imaging, exposure times should be short because children do not generally cooperate and are difficult to restrain. The equipment should work and provide reproducibility in the shortest time range. These short times are only possi-

ble with powerful generators and tubes, as well as optimal rectification and accurate time switches. For older generators, exposure time settings lower than 4 ms, even if desired, should not be used as the prepeak times (>2 ms) interfere with short preset exposures.

(73) Not all generators allow the short exposure times (particularly mobile radiography units) that are required for the higher kVp techniques recommended for paediatric patients. Consequently, low tube voltage is often used for paediatric patients. This results in higher patient doses (Fendel et al., 1989). To overcome the limited capacity of such equipment for short exposure, adequate additional filtration will allow the use of higher tube voltages with the shortest available exposure times. These methods make possible the use of CR and DR, image intensifier photography, and high-speed screen-film systems in paediatric patients.

(74) For these short exposure times, the cable length between the transformer and the tube is important. The cable works as a capacitor and may, depending on its length, produce a significant surge of radiation after the generator has been switched off. This postpeak radiation may last for 2 ms or more (Fendel et al., 1989).

(75) Accurately reproducible exposure times around 1 ms with a rectangular configuration of the dose rate and wavelength of radiation, practically without pre- or postradiation, may be achieved with grid-controlled tubes (Plewes and Vogelstein, 1984).

(76) Radiographic equipment that cannot achieve optimised short exposure times should not be used for paediatric patients. Radiation safety officers or radiation protection advisors should be aware of this and should provide advice to institutions on the suitability of the equipment for this purpose.

4.5. Mobile radiography

(77) Where practicable, all x-ray examinations should be performed in the radiology department due to the higher image quality of stationary equipment and patient dose considerations. Thus, the use of mobile x-ray units should be limited to those patients who cannot be transported to the radiology department.

(78) In addition to the principles outlined above for general radiography, use of portable lead shielding to protect nearby patients should be considered, unless there is sufficient distance between other patients and the radiation source. The recommended minimal distance is 1.5 m.

(79) For low-birthweight and very-low-birthweight premature infants who cannot be transported to the radiology department, mobile units using a very low exposure with little scattered radiation are often used.

(80) Where mobile examinations are frequently performed in a specific unit (i.e. an intensive care unit for older children), the adequacy of the shielding in the surrounding walls and floor should be assessed.

4.6. Digital radiographic systems

(81) In general, digital imaging has allowed a reduction in radiation dose while improving image quality and diagnostic accuracy, but only after appropriate training and careful monitoring of parameters used in the individual radiology department. Patient dose parameters should be displayed at the operator console.

(82) It is important that radiology departments optimise their exposure parameters when a new digital system is installed, and maintain quality assurance regularly thereafter (ICRP, 2004). The advice of a medical physics expert should be sought with regard to optimising equipment parameters for paediatric radiography. One of the simplest methods is to monitor the exposure index of the digital system, which is an objective indicator of radiation exposure incident on the imaging plate (Vañó et al., 2008), but the periodic audit of field-related quantities such as entrance surface air kerma or air kerma–area product should also be performed as part of the quality assurance programme.

(83) Appropriate image processing is crucial in producing the optimal paediatric CR or DR image. Most CR and DR manufacturers now recognise that paediatric patients are unique, and have developed, or are developing, special provisions for paediatric examinations, including image processing (Sanchez Jacob et al., 2009).

(84) The following recommendations to aid dose reduction and image optimisation include those from the second ALARA conference organised by the Society for Paediatric Radiology held in Houston, TX, USA in February 2004 (Willis and Slovis, 2004).

Guidelines to practitioners:

1. There should be a team approach to dose management in CR and DR. The team should include the active participation of a radiologist, medical physicist, radiographer/technologist, manufacturer service engineer, manufacturer applications engineer, and manufacturer imaging scientist.
2. Training of radiographer/technologist in CR and DR technology and practice.
3. Obtain the best patient positioning that is practicable, and collimate adequately.
4. Consider the indication for the study. In the intensive care setting, for example, lines and catheters etc. are inherently of high contrast and there is therefore significant scope for dose reduction when the clinical indication is solely to confirm their position.

4.7. Screen-film systems

(85) Among the technical parameters, the selection of higher speed classes of screen-film system has the greatest impact on dose reduction. In addition, it allows shorter exposure times that minimise motion artefacts, which are the most common cause of blurring in paediatric imaging. The reduced resolution of higher speed screens is comparatively insignificant for the majority of clinical indications. For special purposes such as bony detail of the peripheral skeleton, speed classes of 200–400 can be used; for all other purposes, speed classes of 400–800 are preferred. If different

sets of cassettes are available, one for special indications with screens of lower speed and higher resolution, and one for general use, they should be clearly marked. It should also be noted that similar screen-film systems may vary between manufacturers, and intermediate values of speed classes are common. Therefore, the indicated nominal speed classes in this text can only give approximate guidance.

(86) Users should be encouraged to measure the real speeds of their screen-film systems under standard conditions. The variation in speed that can occur with changes in x-ray beam energy, especially below 70 kV, should be recognised for individual screen-film systems. Users are also encouraged to measure the resolution of their screen-film systems as this varies with the speed class.

4.8. Fluoroscopy

(87) Pulsed fluoroscopy was initially developed to reduce fluoroscopic radiation dose by limiting the time during which the patient was exposed to the x-ray beam, using reduction in the number of exposures per second. Today, generator pulsed and grid-controlled fluoroscopy systems are available. Current grid-controlled pulsed fluoroscopy units use a negatively charged grid interposed between the cathode and the anode of the x-ray tube. The grid can be rapidly switched on and off, which thereby allows appropriate energy electrons generated to be passed intermittently through the grid to produce x-rays. Optimisation of the fluoroscopy pulse widths and careful choice of entrance exposure per pulse during calibration of the unit can permit additional dose savings (Ward et al., 2006).

(88) Results of dose reduction vs image quality evaluation with pulsed fluoroscopy have demonstrated up to 10-fold reduction without significant reduction of contrast or spatial resolution in paediatric radiology (Lederman et al., 2002). In an animal model simulating infant, toddler, and child sizes, the use of pulsed fluoroscopy decreased radiation exposure by a factor of 4.6–7.5 compared with a conventional unit, and there was no significant loss of diagnostic quality (Ward et al., 2006).

(89) Radiation dose can be minimised by keeping the fluoroscopy table as far from the x-ray source as possible to reduce entrance dose to the skin. The image intensifier should be as close to the patient as possible to maximise capture of the number of x-rays.

(90) Scattered radiation emanating from below the table can be minimised by installing a hanging lead drape on the patient table to shield the legs of the operator. New generation sterile drapes impregnated with bismuth or other materials may be used if available. These drapes can markedly reduce doses to the operator and other staff members. They have been shown to reduce operator hand/wrist doses by up to 90%, can be positioned to protect the radiologist from the waist down (King et al., 2002), and have also been shown to reduce operator lens doses (Thornton et al., 2010). If shielding is used for patient protection, it needs to be strategically placed under the patient if an undercouch tube is used, and should not be placed in the direct beam as this will tend to increase the entrance skin doses for those units using AEC features.

(91) For radiological protection during the procedure, fluoroscopy should only be used to evaluate a moving target or structure, and fluoroscopy time should be limited. Still images acquired using last-image hold should be used to review findings and not live fluoroscopy. Pulsed fluoroscopy should be used and, in many instances, 3–8 pulses per second is adequate for guidance and monitoring of a procedure (Connolly et al., 2006). The image intensifier should be properly positioned over the area of interest before fluoroscopy is commenced, rather than positioning during fluoroscopy. Under certain circumstances, virtual collimation helps to perform this positioning without having to use fluoroscopy for this purpose. Tight collimation to the relevant anatomical area is important. Attention should be given to angle the beam away from radiosensitive areas (breast, eyes, thyroid, and gonads) and collimating these areas out of the field if possible. Magnification should be kept to a minimum. Alarm bells for fluoroscopy beyond a certain time or live readouts in the room are useful reminders to limit fluoroscopy time. Air kerma–area product for the procedure should be recorded and compared with benchmark figures, such as those published by the American Association of Physicists in Medicine (American Association of Physicists in Medicine, 1998; Amis et al., 2007).

5. RADIOLOGICAL PROTECTION IN PAEDIATRIC INTERVENTIONAL RADIOLOGY

(92) The use of interventional radiology for paediatric patients is increasing in frequency, and also in the complexity and length of the procedures. As a result, the overall radiation dose to the patient may be greater. Major paediatric interventional procedures, particularly in small infants, should be performed by experienced paediatric interventional operators for both clinical and radiological protection reasons.

(93) The procedure should only be performed when absolutely necessary, and when it is performed, radiation should be minimised or avoided whenever possible by using ultrasound guidance rather than fluoroscopy or CT.

(94) All members of the intervention team should be aware of radiation exposure, and all should undergo training in radiological physics and radiological protection. Moreover, a second, specific level of training in radiological protection for paediatric imaging, additional to that undertaken in general diagnostic radiology, is desirable; this is mandatory in some countries (e.g. European Union countries). Also, specific additional training must be planned when new x-ray systems or techniques are implemented in a centre (ICRP, 2001a; Connolly et al., 2006; Rehani, 2007).

(95) Departments should have a quality assurance programme in place for all equipment under the supervision of a medical physicist (ICRP, 2001a).

5.1. Reducing unnecessary dose to the patient

(96) A notable feature in paediatric fluoroscopy and intervention is the large size of the image intensifiers relative to the size of the neonate, infant, or child. In neonates, infants, and small children, the image intensifier will completely cover the patient and therefore has the potential to increase radiation exposure if collimation is not in use. Also, there is a greater need to use magnification in paediatric patients compared with adults which further increases dose (Connolly et al., 2006). Methods of dose reduction when using fluoroscopy are discussed in Section 4.8.

(97) Complex interventional procedures have been shown to impart high peak skin doses in adults, and high absorbed doses to the exposed organs and tissues in children. The potential clinical effects for single-delivery radiation doses to the skin of adults have been reviewed, and should be brought to the attention of members of the intervention team (Balter et al., 2010). To date, no data are available for children.

5.2. Reducing unnecessary dose to the staff

(98) Special attention should be given to staff exposure that arises from patient scattered radiation. Compared with adults, paediatric patients are smaller, more motion may be encountered during the procedure, and procedures may take longer to perform. Consequently, this may lead to a prolonged fluoroscopy time. Moreover, members of the intervention team may have dose accumulated over many procedures and years of practice (Niklason et al., 1993; Tsapaki, 2001).

(99) Paediatric interventional radiology has unique features that relate to the large range of patient size. To gain access to the small child, it is frequently necessary for the interventional radiologist to come close to, or on occasion enter, the beam. Hand exposure to the primary radiation beam should be avoided, but the hands may inadvertently enter the beam when an unexpected emergent event or complication occurs. Also, the operator's hands may be directly in or immediately adjacent to the beam during a procedure such as a central line placement or abscess drainage.

(100) Attention should be paid to the following points:

- Protective lead apron should be used by all team members in the room, and protection for the eyes (ceiling-suspended screen or lead glasses) should be used by the team members operating close to the x-ray tube and the patient. The appropriate protection of the anaesthetist should also be considered.
- Ceiling-mounted leaded glass or plastic shields or lead glass eyewear with side shields reduce radiation exposure to the eyes of the operator by approximately 90% (Thornton et al., 2010).
- Protective aprons should be well fitted, with arm wings to protect the axillary tail of the breasts for female workers, and a full front and back apron for those moving around in the room.
- Radioprotective gloves can reduce the hand dose from scattered radiation by approximately 40–50%. However, it is noteworthy that the use of such gloves can reduce dexterity and may prolong the procedure. Also, lead gloves will increase the dose if they enter the primary beam by raising the parameters. Slight angulation of the beam off the hands, strict collimation, and careful attention to finger positioning will help reduce operator exposure.
- Foot and leg doses for the operator are increasingly receiving attention as procedures become more complex and longer. Lead table flaps or newer compound material drapes that reduce the dose from scattered radiation to the legs and ankles may be considered.
- Staff dose should be determined with one badge dosimeter under the lead apron and one over the apron at the collar if being used (ICRP, 2001a). The use of radiation ring badges is also important if the procedures performed carry the possibility of the hands falling into the primary beam or on the edge of the primary beam.
- The operator should stand to the side of the image intensifier and, whenever possible, team members should step back so as to reduce radiation dose due to the greater distance from the source (i.e. the inverse square law).
- The use of a power injector instead of hand injection of contrast material has been shown to be the single most effective way to reduce operator dose during angiography (Hayashi et al., 1998). It should be used where possible, and the operator should step away from the patient and/or behind a mobile lead screen during contrast injections. When manual injection is necessary, maximising the distance from the patient as much as catheter length will permit is important to minimise radiation dose.

5.3. Image acquisition using digital angiography or digital subtraction angiography

(101) Image acquisition runs should only be performed if necessary for diagnosis or assessment of outcome after a procedure. The fewest number of frames per second required to achieve the clinical objective should be used, and images should be obtained using the lowest magnification (postprocessing magnification is possible). Tight collimation should always be used to only include the area of interest. Furthermore, last-image hold, image capture, video recording, and digital fluoroscopy runs can be archived in the PACS (Picture Archiving and Communication System) system and subsequently reviewed.

(102) When C-arm equipment is used, it is important to be aware of the proximity of the skin to the x-ray source in the lateral and oblique views, which will result in an increase in patient skin dose. The patient's arms should be raised whenever possible when in the lateral and oblique positions. Where practicable, arm supports should be used to prevent the arm drifting towards the primary beam during long procedures. Field overlap in different projections should be minimised.

6. RADIOLOGICAL PROTECTION OF PATIENTS IN PAEDIATRIC COMPUTED TOMOGRAPHY

6.1. Measurements of computed tomography dose

(103) The CT dose index (CTDI) is the primary measurement in CT. For the reason indicated in Section 2.1, paragraph 7, ICRU (2005) and IAEA (2007) have recommended the use of air kerma instead of absorbed dose to air (CT air-kerma index). Nevertheless, in this publication, CTDI values are given in the data tables as they appear in the literature. CTDI represents the average absorbed dose, along the z axis, from a series of contiguous exposures. It is measured from one axial CT scan (one rotation of the x-ray tube), and is calculated by dividing the integrated absorbed dose by the total beam width. CTDI theoretically estimates the average dose within the central region of a scan volume equivalent in size and attenuating properties to the phantom used in its measurement. CTDI offers a convenient method of estimating this value, and only requires a single scan acquisition, which in the early days of CT saved a considerable amount of time. CTDI can vary across the field of view. For body imaging, CTDI is typically a factor of 2 higher at the surface than at the centre of rotation. The average CTDI across the field of view is given by the weighted CTDI ($CTDI_W$) (Leitz et al., 1995; European Commission, 2000; International Electrotechnical Commission, 2002), where:

$$CTDI_W = 1/3\ CTDI_{100,centre} + 2/3\ CTDI_{100,edge} \quad (1)$$

The values of 1/3 and 2/3 approximate the relative volumes represented by the centre and edge values (Leitz et al., 1995). $CTDI_W$ is a useful indicator of scanner radiation output for a specific kVp and mAs.

(104) The term used to characterise volume exposure is the dose–length product (DLP); a parameter directly derived from the product of the $CTDI_W$ [CTDI (mGy/100 mAs) weighted for central and peripheral locations, i.e. the average CTDI across the field of view] and the length of the scan. The DLP can be measured by the scanner either at the end of the study or even earlier for prospective planning.

(105) $CTDI_{vol}$ is the parameter that best represents the average dose at a point within the scan volume for a particular scan protocol. In helical CT, the ratio of the table travel per rotation to the total beam width is referred to as 'pitch'; hence $CTDI_{vol}$ is equal to $CTDI_W$ divided by the pitch. Thus, whereas $CTDI_W$ represents the average absorbed radiation dose over the x and y directions, $CTDI_{vol}$ represents the average absorbed radiation dose over the x, y, and z directions where the z direction is parallel to the table feed. While $CTDI_{vol}$ estimates the average radiation dose within the irradiated volume of a CT acquisition for an object of similar attenuation to the CTDI phantom, it does not represent the average dose for objects of substantially different size, shape, or attenuation. Additionally, it does not indicate the total energy deposited into the scan volume because this measurement is independent of the length of the scan. The SI unit is milligray (mGy) and the value is required to be displayed prospectively on the console of newer CT scanners (by the World Health Organization, International Electrotechnical Commission, US Food and

Table 6.1. Countrywide surveys of dose estimations for paediatric computed tomography (CT) of the head, chest, and abdomen/pelvis (modified from Thomas, 2011).

CT head	1 (or 0–1) years[†]		5 (or 2–5) years		10 (or 6–10) years	
	$CTDI_{vol}$ 16[*]	DLP 16	$CTDI_{vol}$ 16	DLP 16	$CTDI_{vol}$ 16	DLP 16
UK 2005 (Shrimpton et al., 2005)	35/30	270	50/45	470	65/50	620
Germany 2008 (Galanski et al., 2007)	33	390	40	520	50	710
Switzerland 2008 (Verdun et al., 2008)[‡]	20	270	30	420	40	560
France 2009 (Brisse and Aubert, 2009)	30	420	40	600	50	900
Greece 2009 (Yakoumakis et al., 2009)	-	-	-	650	-	975
Belgium 2010 (Buls et al., 2010)	35	280	43	473	49	637

CT chest	1 (or 0–1) years		5 (or 2–5) years		10 (or 6–10) years	
	$CTDI_{vol}$ 32 (16)[*]	DLP 32 (16)	$CTDI_{vol}$ 32 (16)	DLP 32 (16)	$CTDI_{vol}$ 32 (16)	DLP 32 (16)
UK 2005 (Shrimpton et al., 2005)	6 (12)	100 (200)	6.5 (13)	115 (230)	10 (20)	185 (370)
Germany 2008 (Galanski et al., 2007)	1.7 (3.5)	28 (55)	2.7 (5.5)	55 (110)	4.3 (8.5)	105 (210)
Switzerland 2008 (Verdun et al., 2008)[‡]	2.5 (5)	55 (110)	4 (8)	100 (200)	5 (10)	110 (220)
France 2009 (Brisse and Aubert, 2009)	3 (6)	30 (60)	3.5 (7)	63 (126)	5.5 (11)	137 (274)
Greece 2009 (Yakoumakis et al., 2009)	-	-	-	168 (336)	-	289 (578)
Belgium 2010 (Buls et al., 2010)	4.2 (8.4)	38 (76)	4.7 (9.3)	55.5 (111)	4.5 (9)	72 (144)
USA 2008[§]	4.3 (8.5)	-	4.8 (9.5)	-	5.5 (11)	-

CT abdomen/pelvis	1 (or 0–1) years		5 (or 2–5) years		10 (or 6–10) years	
	$CTDI_{vol}$ 32 (16)[*]	DLP 32 (16)	$CTDI_{vol}$ 32 (16)	DLP 32 (16)	$CTDI_{vol}$ 32 (16)	DLP 32 (16)
UK 2005 (Shrimpton et al., 2005)	-	-	-	-	-	-
Germany 2008 (Galanski et al., 2007)	2.5 (5)	70 (145)	4 (8)	125 (255)	6.5 (13)	240 (475)
Switzerland 2008 (Verdun et al., 2008)[‡]	3.5 (7)	65 (130)	4.5 (9)	150 (300)	6.5 (13)	190 (380)
France 2009 (Brisse and Aubert, 2009)	4 (8)	80 (160)	4.5 (9)	121 (242)	7 (14)	245 (490)
Greece 2009 (Yakoumakis et al., 2009)	-	-	-	420 (840)	-	560 (1120)
Belgium 2010 (Buls et al., 2010)	3.9 (7.8)	50.2 (101)	5.5 (11)	104.5 (209)	4.8 (9.5)	119 (238)
USA 2008[§]	4.3 (8.5)	-	5.0 (10)	-	5.5 (11)	-

CTDI, CT dose index; DLP, dose–length product.

References: Shrimpton et al., 2005; Galanski et al., 2007; Verdun et al., 2008; Brisse and Aubert, 2009; Yakoumakis et al., 2009; Buls et al., 2010.

* For head CT, CTDI and DLP values refer to the 16-cm phantom. For chest and abdomen/pelvis CT, values refer to the 32-cm phantom, followed by the corresponding 16-cm phantom value in parentheses. Data have been adapted from the original publications, expressed according to the 16-cm phantom (Shrimpton et al., 2005; Verdun et al., 2008; Yakoumakis et al., 2009), the 32-cm phantom (Brisse and Aubert, 2009), or both (Galanski et al., 2007).

† Proposed DRLs expressed for children aged 1, 5, and 10 years (Shrimpton et al., 2005; Brisse and Aubert, 2009; Yakoumakis et al., 2009) or using age ranges (Galanski et al., 2007; Verdun et al., 2008). Most paediatric DRL surveys do not include a specific 15-year-old category, although some include an 11–15-year-old group (Galanski et al., 2007; Verdun et al., 2008); the adult DRL in that country, or a value intermediate between adult and 10-year-old DRL, may be considered appropriate for teenagers.

‡ Switzerland subsequently adopted the values from the larger German study (Galanski et al., 2007).

§ Values calculated according to recommendations of the Alliance for Radiation Safety in Pediatric Imaging, based on the future French DRL values for adult abdominal CT recommended by IRSN, the French Institute for Radiological Protection and Nuclear Safety, in 2008.

Drug Administration, and the European Union). The problem when measuring $CTDI_{vol}$ in multidetector CT, especially larger effective beam widths, is that the length of irradiation (tail of the beam) goes beyond the 100-mm length of the pencil ion chamber. There are proposed chambers that are designed to overcome this problem (Dixon and Ballard, 2007).

(106) Some examples of countrywide surveys of CT dose estimations are presented in Table 6.1 as reference levels for CT of the head, chest, and abdomen/pelvis in children.

6.2. Justification/indications

(107) Paediatric brain CT is not indicated after minor trauma to the head, as the prevalence of injuries requiring neurosurgery is low at 0.02% (Teasdale et al., 1990). Furthermore, it was found that brain CT may be omitted in children after head trauma if they fulfilled the following criteria of having normal mental status, acting normally according to the parents (for children younger than 2 years), no loss of consciousness or loss of consciousness for less than 5 s, non-severe injury mechanism, no palpable skull fracture, no signs of basilar skull fracture, no scalp haematoma except frontal, no vomiting, and no severe headache (for children aged 2 years and older) (Kuppermann et al., 2009). Also, the positive CT findings found in children with daily headache or migraine, or with new onset of seizures did not influence therapy or patient outcome (Lewis and Dorbad, 2000; Maytal et al., 2000).

(108) Ultrasonography should generally be the first-line imaging investigation to assess the abdomen in paediatric patients as their slim body habitus allows visualisation of deep abdominal structures. In experienced hands, ultrasonography can provide a great deal of information and may obviate CT; for example, ultrasonography should be the examination first considered in children suspected of acute appendicitis. When ultrasonography is unlikely to provide the answer, the choice of examination is often between CT and MRI, although MRI may not be readily available in some countries and for out-of-hours examinations in some hospitals.

(109) Detailed information about soft tissues, nervous system (with the exception of neonatal head and spine sonography), or bone marrow is often best evaluated with MRI due to the superior contrast resolution.

(110) Malignant disease with higher risk of disease-related mortality may alter considerations of risk for CT radiation exposure. However, with an increasing chance of curative treatment, the added dose from follow-up studies as well as from CT examinations for image-guided therapy should be considered.

(111) Follow-up CT scans should not be performed too early when, according to the known biology of the disease, one cannot yet expect any response to treatment. Justification has to be as rigorous as for the first examination, and alternative modalities may suffice. For follow-up CT studies, the scan volume can also be restricted depending on the clinical indication in order to reduce radiation dose. For example, Jimenez et al. (2006) reported substantial dose reduction (55%) by limiting the scan coverage to just six images per examination for follow-up CT of patients with cystic fibrosis.

(112) Repeated scanning of identical areas (i.e. the use of multiphase CT scans) should be limited and every additional phase justified (Strauss et al., 2010).

6.3. Dose reduction measures in computed tomography equipment

(113) Special consideration should be given to dose reduction measures when purchasing new CT scanners as part of the optimisation process. The advice of a medical physicist should be sought regarding procurement, commissioning, quality control tests etc. Software and hardware developments for dose reduction include tube current modulation, a form of AEC where the tube current can be 'child-sized' according to patient geometry and density. New wide-detector CT scanners enable large volume scanning in minimal time. With dual-source CT scanners, rapid table speeds and high-pitch scanning lead to shorter scan times and have been applied to paediatric chest and cardiac CT to reduce dose exposure substantially. Furthermore, filters for modifying the irradiation beam (e.g. bow-tie filters) improved efficiency of x-ray detectors, and methods to block unnecessary radiation from 'helical overdosing' by dynamic or adaptive collimation are now available. New organ-based dose modulation can reduce the mA over an arc of 120° anteriorly when the patient is supine for dose savings in the breast, thyroid, or lens. Use of the iterative reconstruction technique for image reconstruction is a dose reduction feature available in newer multidetector scanners. New auto kV technology is becoming available, adjusting the kVp to patient geometry and study indication. Finally, new software providing alerts and notifications on scanner consoles may help to prevent excessive doses prior to scanning, and can be used for quality assurance and improvement programmes (Hampton, 2010).

6.4. Optimisation of image quality and study quality

(114) Attention should be paid to both image quality and study quality. As with other imaging modalities, patient preparation should be optimised. For example, selective use of sedation reduces or eliminates patient movement and degradation of image quality. Images may be of excellent quality in terms of detail but fail to provide the necessary information to make a diagnosis without some manipulation such as planar reformations. Objective attributes to quality include image noise and image contrast. For the purpose of minimising radiation dose exposure, noisier images, if sufficient for radiological diagnosis, should be accepted. Much of paediatric CT examination also depends on meticulous contrast administration. Dose reduction efforts must be matched with this critical component in order to maximise the quality/dose ratio. Artefacts are also related to study quality. Adjustable factors such as scan time and pitch may affect the presence or absence of motion artefacts. With the advent of multidetector CT, faster table speed, and gantry rotation, breathing artefacts in paediatric patients may be reduced.

(115) Study quality also depends on the structure or the region being examined. More image noise may be acceptable in skeletal or lung parenchymal examinations than in brain or abdominal examinations. This is due, in part, to the higher contrast differences in the former. Therefore, a chest examination with higher noise may have

the same study quality as an abdominal study with lower noise. Abdominal organs such as the liver, kidney, and pancreas may only show minimal density differences between normal tissues and pathological lesions, and may require a higher patient dose to obtain diagnostic quality. In addition, three-dimensional reconstruction to determine bony outlines for surgical planning may also be done at low dose levels (Vock, 2005).

(116) The acceptable study quality may also be determined by the clinical indication of the study. High-contrast lesions, even small, such as kidney stones, are amenable to low-dose CT techniques in children (Karmazyn et al., 2009). Smaller low-contrast lesions require higher contrast resolution. For example, more image noise may be tolerated in a follow-up study to assess a fracture of the liver than in a study to assess the presence of small liver metastases.

(117) The perception of study quality (ICRP, 2001b) is also related to the display of the data. A study viewed on the CT console may look inferior when viewed on a monitor that is not optimised for viewing a particular examination. The ambient environment for image review also affects perception of study quality.

6.5. Adjustment in scan parameters and optimising dose reduction

(118) As image noise increases with x-ray beam attenuation, which in turn is affected by the distance that x-rays traverse through the patient body region being scanned, scanning parameters (mA, kVp) should be adjusted to adapt dose to patient weight or age (Frush et al., 2002; Moss and McLean, 2006). Alternatively, AEC techniques/systems (Greess et al., 2002, 2004) can be used to reduce the CT radiation dose to paediatric patients.

6.5.1. Tube current–exposure time product (mAs)

(119) Tube current–exposure time product, also called 'tube loading' (IAEA, 2007), affects image noise. It has a linear relationship with radiation dose (i.e. doubling tube current–exposure time product doubles radiation dose). However, the relationship between tube current–exposure time product and noise is more complicated (i.e. increasing tube current–exposure time product reduces image noise proportional to the square root of tube current–exposure time product). For example, a fourfold increase in tube current–exposure time product (and dose) results in half the image noise. Several authors have shown that to reach the same photon flow at the detector, tube current–exposure time product (mAs) can be reduced significantly in paediatric patients compared with adults. At 120 kVp, Huda et al., 2000 reduced the 1300 mAs for 120-kg body weight to 200 mAs for 70 kg and 17 mAs for 10 kg. Boone et al., 2003 reached a constant contrast-to-noise ratio for abdominal protocols when current was reduced from 100% for 28 cm (in an adult phantom) to 56% at 25 cm, 20% at 20 cm, and 5% at 15 cm (in different paediatric phantoms).

(120) Relatively low tube currents have been recommended for CT of the chest. Lucaya et al. (2000) found that low-dose, high-resolution CT provided a significant

reduction in radiation dose (72% for 50 mA and 80% for 34 mA) and also good-quality images of the lung with 50 mAs in uncooperative paediatric and young patients, and 34 mAs in cooperative paediatric and young patients. Rogalla et al. (1999) recommended a range of tube currents from 25 to 75 mA (for a 1-s rotation time) for spiral CT, depending on the age of the patient. It is important to realise that one of the risks of low-dose scanning in addition to the possibility of missing abnormalities is that a false-positive finding may not have occurred with a higher tube current–exposure time and a lower noise level.

6.5.2. Tube voltage (kVp)

(121) The kVp needed to penetrate the body of a paediatric patient is lower than that of an adult as the physical size of the paediatric patient is smaller. Therefore, 120 kVp is used in adult CT studies, whereas 100 kVp, and sometimes 80 kVp, is adequate for paediatric patients. Lower kVp without increased mAs causes an increase in noise. However, with higher contrast, higher noise can be tolerated, thus resulting in a dose reduction. This lower kVp may also improve the effect of iodinated contrast agents and is therefore suggested for CT angiography. Excessive lowering of the kVp may cause beam-hardening artefacts (Verdun et al., 2004). Use of 80 kVp is suggested for infants under 5 kg by Vock (2005). Using phantom studies, Yu et al. (2011) suggested tube potentials of 80 kVp and 100 kVp for <10 kg and 10–20 kg weight, respectively, for paediatric chest and abdominopelvic CT. New scan technology is becoming available with 70-kVp options which may have unique benefits for the paediatric population.

(122) The use of weight-adapted paediatric CT protocols has been suggested (Frush et al., 2002; Cody et al., 2004; Verdun et al., 2004; Vock, 2005). Some examples of suggested paediatric CT protocols are included in Table 6.2 (Pages et al., 2003; Verdun et al., 2004; Vock, 2005).

6.5.3. Slice thickness

(123) While the small size of a child requires relatively thinner slices compared with adults in order to improve spatial resolution, using identical exposure with thinner slices compared with thicker slices will automatically increase noise. This has been evaluated in chest CT of children with cystic fibrosis where 0.5-mm thin sections were used instead of 1.0-mm sections, providing diagnostic acceptability for the depiction of bronchovascular structures at lung window settings and reducing dose (0.14 mSv ± 0.04 vs 0.19 mSv ± 0.03) (O'Conner et al., 2010). Keeping the noise level constant requires an increase in mAs, and consequently in radiation exposure, that is inversely proportional to the square of the slice thickness. Thus, reduction of thickness to one half requires an increase in mAs, by a factor of 4. Scanners with four detector rows are less dose efficient than single-row detectors, and need relatively high dose levels for thin slices. With four detector rows or more, this phenomenon is less important due to new detector technology and changes in scanner geometry (Thomton et al., 2003).

Table 6.2. Examples of suggested paediatric computed tomography (CT) protocols (Pages et al., 2003; Verdun et al., 2004; Vock, 2005).

Weight (kg)	$CTDI_{vol}$ (mGy)	kV	mAs
Abdomen pitch 0.75			
2.5–5	7.1	80	72
5–15	9.4	100	56
15–30	14.0	120	64
30–50	18.5	120	96
Age (years)	$CTDI_W$ (mGy)	DLP (mGy cm)	
Brain/chest			
<1	25/20	180/150	
5	25/25	200/200	
10	50/30	750/600	
Upper/lower abdomen			
<1	20/20	330/170	
5	25/25	360/250	
10	30/30	800/500	

CTDI, CT dose index; DLP, dose–length product.

6.6. Protective shielding

(124) The practice of using local protective shielding varies between institutions. Protocols should be tested specifically for each scanner as one approach is not appropriate for all scanners, and if not used properly, shielding may even increase radiation dose.

(125) Local superficial protective devices using bismuth may be considered in girls to protect the breast tissue where possible (Coursey et al., 2008). However, it is important to note that bismuth protection should only be placed after the scout view (or AEC prescanning) is performed so that the system does not inappropriately increase tube current in the area of the shield. Other devices to protect the lens, thyroid, and gonads from direct or scatter radiation have been suggested. The eyes should be shielded if the examination and the diagnosis is not affected by appropriate shielding material (e.g. bismuth shields) or lead-equivalent eye glasses for x-ray examinations involving high absorbed doses in the eyes (e.g. for CT of the brain and facial bones when angulation of the gantry is not sufficient to keep the orbits outside the examination volume). Lead-equivalent eye glasses should be used with caution, however, as the radiation protection rating of lead-equivalent eye glasses has not been standardised internationally to date. If the patient is cooperative, the absorbed dose can be reduced by 50–70%.

(126) Streak artefacts and increased noise may result from suboptimally placed shielding (e.g. too close to the surface of the skin or not smoothly positioned over the surface). It is recommended that the shield needs to be appropriately placed with enough distance to minimise the subjacent artefact (Kim et al., 2010).

(127) Thus, some authors and institutions have recommended that shielding should not be used on patients, and have instead suggested that in many situations, using proper field size limitation and appropriate tube current modification, signifi-

cant overall reductions in dose can be achieved even without the use of shielding apparatus (Colombo et al., 2004; Geleijns et al., 2006; Kalra et al., 2009).

6.7. Principles for dose reduction in paediatric computed tomography (Vock, 2005)

(128) The following strategies have been recommended to accomplish the objective of dose reduction in paediatric CT, including rigorous justification of CT examinations, acceptance of images with greater noise if diagnostic information can be obtained, optimisation of scan protocols, scanning of minimum length as needed, and reduction of repeated scanning of an identical area.

a. Rigorous justification of CT studies.

- In childhood, alternative imaging modalities such as ultrasonography and MRI should be considered. However, the risks of anaesthesia sometimes required for children undergoing MRI examinations should also be considered.

b. Prepare the patient.

- In young children in particular, interaction is not just with the patient but also with the parents, who, with provision of lead aprons and instructions to stay outside the primary beam, may ease the child's discomfort by staying with the child throughout the procedure.
- Child-friendly environments can also reduce anxiety in children.
- Specially trained staff experienced in dealing with children are very helpful in improving the quality of the study and in preventing repeat scanning with additional exposure.
- If an intravenous line is required, it should be placed well before the examination.
- Placement of necessary protective shielding.

c. Accept image noise as long as the scan is diagnostic.

- It is the task of the radiologist to go to the limits (i.e. to accept as much noise as the medical question allows) (Donnelly et al., 2001).
- The use of postprocessing can help reduce the dose while maintaining the signal-to-noise ratio (reconstruct thicker slices of 3–5 mm for interpretation). The thicker slice images have reduced noise compared with thinner slice images, while the thinner slice images can be used to look at critical details and to obtain two- and three-dimensional reformatted images.

d. Optimise scan parameters.

- Different scanners have different geometry making direct comparison of kVp and mA problematic. The shortest rotation time is generally appropriate in paediatric CT, and this will minimise motion artefacts.
- Tube current and kVp should be adjusted for the size of the patient.

- xy plane (angular) dose modulation: This was introduced to overcome the fact that the human body is not usually round. To achieve the same signal-to-noise ratio, less radiation is generally required in the y-axis (anteroposterior) than in the x-axis (left to right). xy plane modulation reduces the mAs by 20–40% depending on the area examined, and it should be used if available and suitable.
- z-axis (longitudinal) modulation: In the longitudinal axis of the body (z-axis), the radiation needed for an adequate signal-to-noise ratio will vary with the density of structures at various locations in the patient. The z-axis modulation is steered either from the CT localiser view or interactively, and should be used where possible.

e. Limit scan coverage.
This applies for both the scout view and the rotational study.

f. Avoid non-justified multiple scans of the same area.

- If repeat scans are necessary, consideration should be given to limiting these to the smallest volume possible or performing them at a lower dose that will not obscure the additional information expected. Multiphase CT examinations in children should be justified in each case.
- A number of medical reasons may require repeat scans of the same area:
  - Pre- and postcontrast enhanced scan after intravenous bolus injection.
  - Correct timing of scans (e.g. bolus tracking) using a test bolus or repetitive scanning of one plane at low dose for bolus triggering of the proper diagnostic scan. In this case, the sequential scans can be very low dose (e.g. 5 mAs).
  - Dynamic enhanced studies, including arterial, venous, and/or excretion phases of organs such as the kidneys.
  - Supine and prone scans to demonstrate positional gravitational effects in the lungs.
  - Lung scans in inspiration and expiration to detect air trapping.
  - CT-guided intervention with fluoroscopy.
  - Screening with thick slices and subsequent detailed scanning with thin slices.

7. SUMMARY AND RECOMMENDATIONS

- Justification of every examination involving ionising radiation, followed by optimisation of radiological protection, is important in every patient, and especially in paediatric patients in view of the higher risk of adverse effects per unit of radiation dose compared with adults.
- According to the justification principle, if a diagnostic imaging examination is indicated and justified, this implies that the risk to the patient of not doing the examination is greater than the risk of potential radiation-induced harm to the patient.
- Imaging techniques that do not employ the use of ionising radiation should always be considered as a possible alternative.
- Optimisation of radiological protection involves optimised functioning of radiological equipment and quality control, ensuring radiological equipment and technical parameters are adequately tailored for paediatric patients, and the implementation of DRLs to assist in the optimisation process.
- Quality criteria implementation and regular audits should be instituted as part of the radiological protection culture in the institution.
- Attention should be paid to good radiographic technique including positioning and immobilisation of paediatric patients, field size, and protective shielding. Radiographic exposure parameters should be specially tailored for patient size and age.
- As most imaging equipment and vendor-specified protocols are structured for adults, modifications of equipment and exposure parameters may be necessary for paediatric use. Advice of medical physicists should be sought, if possible, to assist with installation, setting imaging protocols, and optimisation.
- Interventional procedures should be performed by experienced paediatric interventional staff due to the potential for high patient radiation dose exposure, and additional training in radiological protection is recommended to protect both patients and staff.
- For CT, dose reduction should be optimised by adjustment of scan parameters (mA, kVp, and pitch) according to patient weight or age, and weight-adapted CT protocols have been suggested and published. For the purpose of minimising radiation exposure, noisier images, if sufficient for radiological diagnosis, should be accepted. Optimised study quality also depends on region scanned and study indication. Other dose reduction strategies include restricting multiphase examination protocols, avoiding overlapping of scan regions, and only scanning the area in question. Furthermore, study quality may be improved by image postprocessing to facilitate radiological diagnoses and interpretation.

ANNEX A. GUIDELINES FOR THE APPROPRIATE USE OF PAEDIATRIC RADIOLOGICAL PROCEDURES

The following examples are adapted from the guidelines for referring doctors and radiologists published by the Royal College of Radiologists (2007, www.rcr.ac.uk).

A.1. Central nervous system

- After head injury in a child, skull radiography is not indicated except in suspected non-accidental injury (child abuse). Depending on a number of clinical trauma features of accidental brain injury, CT may be indicated.
- For congenital disorders of the head or spine, MRI is indicated unless there is need for general anaesthesia or need to delineate bone detail which may make CT the preferred modality.
- In cases of abnormal head appearance (e.g. hydrocephalus with open fontanelle), ultrasound is indicated with the exception of need for three-dimensional reconstruction prior to cranial surgery which necessitates a CT examination. For possible shunt malfunction in operated hydrocephalus, radiography of the whole valve system is indicated.
- In patients with epilepsy, skull radiography is not indicated. These recommendations are the same for deafness, developmental delay, or suspected cerebral palsy.
- Headache, mastoiditis, or suspected sinusitis (the sinuses are poorly or not developed below 5 years of age) are not normally accepted indications for radiography. Low-dose CT or preferably MRI are specialised investigations.

A.2. Neck and spine

- In a child with torticollis without trauma, ultrasound is indicated while MRI, radiography, or CT are only indicated under specific circumstances when the clinical findings are atypical or longstanding.
- Spina bifida occulta is not an indication for any imaging as it is a common variation. Ultrasound or MRI is indicated if neurological symptoms or signs are present.

A.3. Musculoskeletal system

- Suspicion of non-accidental injury (child abuse) is an indication for skeletal survey if below 2 years of age. However, it is recommended that a skeletal survey should be undertaken by a radiographer/technologist trained in paediatric practice, and that a radiologist should supervise the examination and provide advice about supplementary views as necessary.
- Routine x-ray of the opposite side for comparison after limb injury is not justified.

- X-ray of the left wrist/hand for bone age determination is indicated for short stature or growth failure.
- In children with irritable hip or limping, ultrasound is indicated to exclude or confirm a joint effusion and to guide diagnosis and also treatment. X-rays or nuclear medicine examinations are only indicated in the case of a negative ultrasound. MRI is a specialised investigation in cases of suspicion of an unusual pathology such as osteomyelitis, avascular necrosis, or tumours.
- For symptoms or signs of focal bone pain, radiography is indicated. Ultrasound can be helpful in suspected osteomyelitis and there is increasing use of MRI in these patients.
- Clicking hip in infants between 2 and 5 months of age should be assessed with ultrasound. Radiography is only useful when no expertise in ultrasound is available or in infants over 5 months of age.
- Radiography is not indicated in Osgood–Schlatter's disease, and the soft tissue swelling should be assessed clinically.

A.4. Cardiothoracic system

- Chest x-rays are not indicated initially for acute chest infections or recurrent productive cough, but only if symptoms persist despite treatment, in severely ill patients, or in patients with fever of unknown origin.
- Radiography may be indicated for suspected inhalation of a foreign body. There is wide variation in local policy about the use of expiratory films, fluoroscopy, and CT.
- Chest x-rays are not routinely indicated for wheezing or acute stridor. Epiglottitis is a clinical diagnosis, but lateral neck x-ray may be of value specifically in children with a stable airway in whom an obstructing foreign body or retropharyngeal abscess is suspected.
- Chest x-rays are not routinely indicated for a heart murmur. Specialist referral or echocardiography should be considered.

A.5. Gastrointestinal system

- Ultrasound has high sensitivity in the diagnosis of intussusception, but it is operator dependent; it should be used as far as possible for suspected intussusception.
- For swallowed foreign bodies, chest x-ray including neck should be performed. Abdominal x-ray is only indicated to confirm the suspected ingestion of sharp foreign bodies, or toxic or poisonous substances (e.g. batteries).
- Minor trauma to the abdomen is not routinely an indication for abdominal radiography, unless there are positive physical signs suggestive of intra-abdominal pathology or injury to the spine or bony pelvis. CT remains the primary

imaging investigation of choice for blunt abdominal trauma, but ultrasound may be useful in follow-up of known organ injuries. Major abdominal trauma should be handled according to the same local policy as for adults.

- Ultrasound is the modality of choice in projectile vomiting to rule out hypertrophic pyloric stenosis. Upper gastrointestinal contrast examinations are not normally indicated for recurrent vomiting or simple gastro-oesophageal reflux.
- Abdominal radiography in constipation is not routinely indicated; if Hirschsprung's disease is suspected, specialist referral plus biopsy is preferred.
- When an abdominal mass can be palpated, initial ultrasound is indicated. If the presence of a mass is confirmed, further imaging, either by MRI or CT, may be performed, preferably in a specialist centre.

A.6. Genitourinary system

- Continuous wetting should be evaluated with ultrasound. Intravenous urography (IVU) should only be performed specifically for confirmation of ectopic infrasphincteric ureters in girls with duplex systems. MRI urography, if available, is an alternative to IVU.
- X-ray of the lumbosacral spine is indicated in children with abnormal neurology or skeletal examination, in addition to those with bladder wall thickening/trabeculation shown on ultrasound or neuropathic vesicourethral dysfunction on video-urodynamics.
- Ultrasound is indicated in case of impalpable testis, but MRI might be helpful in cases of intra-abdominal testis. Laparoscopic evaluation is increasingly utilised.
- Antenatal diagnosis of urinary tract dilatation should be evaluated with ultrasound, but a low threshold for specialist referral is recommended.

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