Safety Reports Series

No. 71

Radiation Protection in Paediatric Radiology

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RADIATION PROTECTION IN PAEDIATRIC RADIOLOGY

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SAFETY REPORTS SERIES No. 71

RADIATION PROTECTION IN PAEDIATRIC RADIOLOGY

INTERNATIONAL ATOMIC ENERGY AGENCY
VIENNA, 2012

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PO Box 100
1400 Vienna, Austria
fax: +43 1 2600 29302
tel.: +43 1 2600 22417
email: sales.publications@iaea.org
http://www.iaea.org/books

Printed by the IAEA in Austria
December 2012
STI/PUB/1543

IAEA Library Cataloguing in Publication Data

Radiation protection in paediatric radiology. — Vienna : International Atomic Energy Agency, 2012.
p. ; 24 cm. — (Safety reports series, ISSN 1020–6450 ; no. 71)
STI/PUB/1543
ISBN 978–92–0–125710–9
Includes bibliographical references.

1. Radiological, medical — Safety measures. 2. Pediatric radiology — Safety measures. 3. Diagnostic imaging. I. International Atomic Energy Agency. II. Series.

IAEAL 12–00780

FOREWORD

Over the past decade and a half, special issues have arisen regarding the protection of children undergoing radiological examinations. These issues have come to the consciousness of a gradually widening group of concerned professionals and the public, largely because of the natural instinct to protect children from unnecessary harm. Some tissues in children are more sensitive to radiation and children have a long life expectancy, during which significant pathology can emerge. The instinct to protect children has received further impetus from the level of professional and public concern articulated in the wake of media responses to certain publications in the professional literature.

Many institutions have highlighted the need to pay particular attention to the special problems of protecting paediatric patients. The International Commission on Radiological Protection has noted it and the IAEA's General Safety Requirements publication, Radiation Protection and Safety of Radiation Sources: International Basic Safety Standards (BSS), requires it. This need has been endorsed implicitly in the advisory material on paediatric computed tomography scanning issued by bodies such as the US Food and Drug Administration and the National Cancer Institute in the United States of America, as well as by many initiatives taken by other national and regional radiological societies and professional bodies.

A major part of patient exposure, in general, and paediatric exposure, in particular, now arises from practices that barely existed two decades ago. For practitioners and regulators, it is evident that this innovation has been driven both by the imaging industry and by an ever increasing array of new applications generated and validated in the clinical environment. Regulation, industrial standardization, safety procedures and advice on best practice lag (inevitably) behind industrial and clinical innovations. This Safety Report is designed to consolidate and provide timely advice on dealing with the special problems involved.

The approach adopted is developed within the IAEA framework of statutory responsibility to establish standards for the protection of people against exposure to ionizing radiation and to provide for the application of these standards. The BSS issued by the IAEA require the radiation protection of patients undergoing medical exposures through justification of the procedures involved and optimization of protection and safety.

This challenge is taken up here by adding paediatric radiology to the areas dealt with in recent IAEA publications. These are specifically Safety Reports Series Nos 39 and 40 on diagnostic radiology and nuclear medicine, respectively, and Safety Reports Series Nos 58–61 and 63 on newer medical imaging

techniques and other initiatives in justification of procedures and optimization of protection and safety.

The advice of the IAEA is intended in particular for professionals, practitioners, and teachers and trainers in the area, as well as physicians referring children for examinations. Resource materials and training materials are available cost free on the IAEA's Radiation Protection of Patients web site (http://rpop.iaea.org).

The IAEA wishes to thank V. Donoghue, J. Malone and O. Ciraj-Bjelac for their assistance in reviewing the drafts of this publication at different stages of preparation. The IAEA officer responsible for this publication was M.M. Rehani of the Division of Radiation, Transport and Waste Safety.

EDITORIAL NOTE

CONTENTS

1. INTRODUCTION

1.1. BACKGROUND

Paediatric radiology involves imaging individuals with diseases of childhood and adolescence. The age range involved is defined differently in different health care systems. The spectrum of diseases includes conditions specific to very young children and many conditions common in the adult population. Figures derived from the United Nations Scientific Committee on the Effects of Atomic Radiation (UNSCEAR) suggest that about 250 million paediatric radiological examinations (including dental examinations) per year were performed worldwide between 1997 and 2007 [1]. Children undergoing these examinations require special attention, both because of the diseases specific to childhood and the additional risks to them. In addition, children need special care, in the form provided by parents, carers and comforters, as well as care that has to be provided by specially trained health professionals.

Some tissues in children are more sensitive to the damaging effects of ionizing radiation than those in adults and special attention has to be paid to the amounts of radiation used [2–8]. A useful general summary of some of the reasons for this is given in Table 1 (taken from Ref. [9]). The extent of the overall unnecessary paediatric dose and risk is uncertain but is currently a matter of considerable concern [10, 11].

Organs and tissues are closer together in small children and, hence, are harder to exclude from the primary beam and to protect from scatter. They are also distributed differently and are more susceptible to radiation damage. For example, a computed tomography (CT) study of the lower extremities in an adult will encounter almost exclusively fatty tissue in the bone marrow. In a child, a significant proportion of the red marrow will be exposed, which is a much greater cause for concern [11]. In addition, children have thinner layers of abdominal visceral fat; hence, the natural contrast usually available in adults is much reduced. Most radiation induced neoplasms do not manifest until several years after exposure, so adult patients may die of other causes before they develop. Owing to their longer life expectancy, children have a greater chance of living long enough to develop a radiation induced neoplasm.

In practice, there is relatively little quantitative literature and audit of practice on the protection of paediatric patients from radiation during diagnostic procedures. This makes it difficult to gain knowledge and to justify whether this protection is working. The benefits of a procedure need to be balanced against the possibility of damage occurring, although this can be difficult to quantify. However, even with a

TABLE 1. REASONS FOR GREATER RISK IN PAEDIATRIC AS COMPARED WITH ADULT COMPUTED TOMOGRAPHY [9]

Reason	Explanation
Higher biological sensitivity at same dose	More proliferating tissue; different tissue distribution
Longer life expectancy	Late manifestation of radiation induced cancers
Increase in dose and effective dose due to technical factors in radiology	Equipment often poorly adapted to paediatric radiology; smaller size and close proximity of organs in children

dearth of literature, there is much that can be achieved. For example, relatively simple advice on the following will yield dose savings:

— Awareness of the special problems of patient positioning;
— The need for immobilization techniques (including help from parents, friends and technical aids);
— The use of image quality assessment;
— The importance of gonad protection;
— The value and proper use of collimation;
— The use of appropriate projections to minimize dose to high risk tissues;
— The use of appropriate filters, mA modulation and/or special paediatric factors with CT.

This publication brings together and summarizes the available advice on good practice in this area.

1.2. OBJECTIVE AND SCOPE

This publication provides guidance to radiologists, other clinicians and radiographers and/or technologists involved in diagnostic procedures using ionizing radiation with children and adolescents. It will also be of value to medical physicists and regulators. It is focused on the measures necessary to provide protection from the harmful effects of radiation by meeting the requirements established in the International Basic Safety Standards (BSS) [2] and by according the necessary priority to this area. The emphasis throughout is on the special requirements of paediatric radiology with, where it is felt to be helpful or necessary, limited restatement of operational aspects of patient and staff protection widely used elsewhere in radiology.

Facility design, the physics of equipment, and radiology information system and/or picture archiving and communication system (RIS/PACS) issues are not addressed, with the exception of the section on procurement and management of equipment in Section 3. This is included as paediatric facilities do not always enjoy the support available to larger units for procurement purposes. In keeping with current developments, additional attention is given to justification, as is evident in IAEA and European Commission (EC) activities, and in the Image Gently Campaign [10].

The only mandatory statements in this text are the requirements quoted from the BSS [2]. Guidance provided here in the form of 'should' statements, or simply in the present tense indicative, describing good practices, represents expert opinion but does not constitute international consensus recommendations on how to meet the relevant requirements.

There are certain requirements in the BSS [2] that, when applied to specific practices, can be fulfilled mainly by means of one practical measure. In such cases, the regulatory body may need to use a 'should' statement, which means that licensees should take this measure; if another measure is intended, an equivalent level of protection and safety should be achieved. In other cases, there may be more than one possible option. In such cases, the regulatory body would mention them or describe them.

1.3. STRUCTURE

Section 2 presents the general framework for radiation protection of patients and staff in paediatric radiology, and includes a discussion on the justification of medical exposures, which are sometimes neglected in radiology. This section also deals with optimization; dose limits and constraints; occupationally exposed workers, carers and comforters; pregnancy; staff training; and research. Pertinent aspects of equipment procurement and/or management, and of immobilization devices are addressed in Section 3. The main body of the text is a series of sections treating the major radiological imaging modalities including:

— General, mobile and dental radiography, including film and/or digital systems (Section 4);
— Fluoroscopy and interventions, both diagnostic and/or therapeutic (Section 5);
— CT (Section 6);
— Diagnostic nuclear medicine (Section 7).

With each, the issue of justification is considered and practical information is provided, where possible, on optimization of protection and safety, including the doses involved and their moderation and/or control.

2. FRAMEWORK FOR RADIATION PROTECTION IN PAEDIATRIC RADIOLOGY

2.1. BASIS FOR RADIATION PROTECTION IN PAEDIATRIC RADIOLOGY

The basis for radiation protection in paediatric radiology is well recognized. It includes the requirement that there be a clear delineation of responsibility extending from the level of the board of governors of the facility (e.g. a hospital or clinic) involved, to the operational level. The requirement for involvement of the hospital management and the need for a good operational structure which can deliver both the required technical and scientific advice and its effective implementation in the clinical environment is also well recognized [2, 3, 12].

It is key to successful development, in this regard, that the head of department be aware of and accept and discharge his or her responsibilities with respect to radiation protection.

The licensee of the paediatric radiology facility, through the authorization issued by the regulatory body, has the prime responsibility for applying the relevant national regulations and meeting the conditions of the licence. The licensee retains overall responsibility, but may appoint other people to carry out actions and tasks related to these responsibilities. In particular, the radiological medical practitioner[1], the medical physicist[2], the medical radiation technologist[3] and the radiation protection officer[4] (RPO) all have key roles and responsibilities in radiation protection in the paediatric radiology facility.

A medical physicist needs to be available to fulfil, oversee or advise on radiation protection requirements for imaging, calibration, dosimetry and quality

[1] The term 'radiological medical practitioner' is defined in the BSS [2] (see Appendix III), and is used to cover the range of health professionals that include radiologists, nuclear medicine physicians, radiation oncologists, cardiologists, dentists and other specialists that might use radiation. In this publication, the term 'radiological medical practitioner' is used when the more general sense is appropriate and, at other times, the names of specific health professionals are used when this gives better clarity.

[2] The term 'medical physicist' is defined in the BSS [2] (see Appendix III).

[3] The term 'medical radiation technologist' is defined in the BSS [2] (see Appendix III), and is used to cover the range of health professionals that are known by various terms in different parts of the world, and include radiographers, radiation technologists and nuclear medicine technicians.

[4] The term 'radiation protection officer' is defined in the BSS [2] (see Appendix III).

assurance in paediatric radiology, and an RPO has to be available for radiation protection matters with respect to staff and members of the public and to advise on general regulatory requirements for radiation protection. In many cases, these two roles may be carried out by one person, where that person is recognized as having the requisite specialist competence for both roles. The medical physicist and the RPO also have to be closely involved in the development of the department's operational arrangements and its safety policies, and in monitoring, reviewing and revising these arrangements.

In practice, a radiation protection committee is normally required, with the various stakeholders, including management, represented. A member of the department is usually appointed as RPO. The RPO's responsibilities include monitoring the implementation of the committee's policies. When a department is sufficiently large to allow roles to be differentiated, the RPO may not hold key departmental line management roles, such as head of department or chief medical radiation technologist.

In practice, radiation protection relies on meeting requirements [2] that apply three principles adopted in most regulatory systems throughout the world [13, 14]. These requirements concern:

— Justification of the activities or practices involved;
— Optimization of protection and safety in the activities or practices involved in terms of risks, costs, benefits, etc.;
— Limitation of the doses received by various groups, including workers and the general public.

Discussions of various aspects of these arrangements are available from many sources [2–4, 12–14].

2.2. JUSTIFICATION

2.2.1. General considerations

The benefits of many procedures that utilize ionizing radiation are well established and well accepted both by the medical profession and society at large. When a procedure involving radiation is medically justifiable, the anticipated benefits are almost always identifiable and are sometimes quantifiable. On the other hand, the risk of adverse consequences is often difficult to estimate and quantify. In its 1990 and 2007 recommendations, the International Commission on Radiological Protection (ICRP) stated as a principle of justification that "Any decision that alters the radiation exposure situation should do more good than

harm" [12–14]. A stronger position on justification of medical exposures is often taken to the effect that the 'good' (i.e. the benefit) has to substantially outweigh any risks that may be incurred, in part because of the uncertainty of the risks [15].

The ICRP has recommended a multi-step approach to the justification of patient exposures, and this is further discussed in Section 2.2.3 [12–14]. In the case of the individual patient, justification normally involves both the referring medical practitioner (who refers the patient, and may, for example, be the patient's physician and/or surgeon) and the radiological medical practitioner (under whose responsibility the examination is conducted) (see Appendix III).

Since 2007, there has been a heightened sensitivity to justification in paediatric radiology. This has become more visible due to both concerns emerging in scientific publications and events reported in the media [16–19]. More recently, the IAEA and the Alliance for Radiation Safety in Pediatric Imaging (the Image Gently Campaign) have articulated these concerns and have provided both a structured approach to solutions and a forum for development in the area [10, 20].

Justification for radiation exposure almost inevitably involves a physician familiar with the patient and the medical history. Normally, an appropriately qualified medical or dental practitioner (e.g. a radiologist, cardiologist or dentist) takes overall responsibility for the conduct of an examination and needs to work in close cooperation with the referring physician(s) in order to establish the most appropriate procedure for the management of the patient.

It is particularly important with infants and children that the feasibility of alternative techniques that do not use ionizing radiation (e.g. ultrasound and magnetic resonance imaging (MRI)) be considered. This is even more important in children with chronic diseases. Some jurisdictions, for example, in the European Union (EU), add a requirement that where an examination cannot be justified it should be prohibited [5]. An effective way of improving good justification practice is to include it as part of a programme of clinical audit [17, 21].

2.2.2. The physician's and radiologist's knowledge

Education and training of both referring physicians and radiologists play a crucial role in ensuring that justification works well in practice. Effective justification requires that these physicians possess knowledge of the particular case and its circumstances. Current experience and the published literature suggest that, in many clinical settings, the referring practitioner may have limited awareness of the radiation doses and risks involved [15–18]. As advocated by the Image Gently Campaign and many individual workers, it is essential that those actually performing the procedures be well informed [10, 20–24].

In practice, knowledge of the situation always has to be viewed in the context of what can reasonably be expected. New knowledge can and needs to be acquired as developments occur. The knowledge required for justification includes:

— The clinical history, including examinations already performed;
— Potential benefits of the action;
— Awareness of short term and long term consequences, including the risks;
— Up to date knowledge of any available alternative actions;
— Knowledge of the consequences of not taking any action;
— Knowledge of referral guidelines and/or acceptability criteria where they are available.

2.2.3. Justification, the ICRP and the procedure

The ICRP identifies three levels at which justification operates [12, 14]. Level 1 deals with the use of radiation in medicine in general. In practice, such use is accepted as doing more good than harm to the patient, and its justification is taken for granted. Level 2 deals with specified procedures with a specified objective (e.g. chest radiographs for patients showing relevant symptoms). The aim at this level is to judge whether the procedure will improve diagnosis or provide necessary information about those exposed. Finally, Level 3 deals with the application of the procedure to an individual (i.e. whether the particular application is judged to do more good than harm to the individual patient). In practice, all individual medical exposures need to be justified in advance, by taking into account the specific objectives of the exposure and the characteristics of the individual patient.

2.2.4. Justification and the patient

Each person, including children and adolescents, has dignity, and is entitled to a reasonable expectation of health. Respect for the dignity of each individual is grounded in contemporary philosophical, social and legal thinking on the nature of the person [15, 17, 18]. It has implications for the level of involvement of the individual and/or their guardian or legal proxy in deciding whether a radiological examination is required or appropriate. Thus, the individual is entitled to know what is to happen [15, 22]. Parents of some children may desire to have information about radiation risk, in particular for high dose examinations such as CT or fluoroscopy guided interventions. Responsibility for providing this information could lie with both the clinician requesting the study and the radiologist. In some situations, the patient may be referred to a medical physicist for dose estimation.

In spite of concern, some patients may misinterpret radiation risk and may refuse a useful or potentially life saving examination for fear of radiation. There is evidence that explaining the risk will not dissuade patients from undergoing the examination, even when the risk is explained to parents of children in the radiation sensitive age group [23, 24]. However, this may not be universally true and will depend upon the local conditions of societal and individual perception of radiation risk. A brief information handout can improve parental understanding of the risk related to exposure to ionizing radiation, without causing parents to refuse studies recommended by the referring physician [10, 24]. Information on risk to children undergoing high dose examinations may not interfere with appropriate care and may improve parental understanding.

Alternative approaches that induce confidence are likely to be very powerful. These include assurance that the CT facility is certified by an appropriate body that oversees radiation doses to patients, that there is a system in place for regular monitoring of radiation doses to patients and comparing with national or international standards, and maintaining doses within the reference levels. Patients and parents are likely to be satisfied more by the availability of quality control and dose management mechanisms being in place rather than by information on radiation doses that the patient may not understand. A programme of informing parents about the radiation risks associated with relatively high dose procedures and the benefits of the procedure is a good practice.

2.2.5. Justification of medical exposures and dose limits

The ICRP has recommended that dose limits not be applied to medical exposures and, even with the higher radiation sensitivity of children, this recommendation is also applied to paediatric radiology. It is based on the fact that the exposed individual will derive benefit from the procedure, provided it has been properly justified. The BSS state that dose limits are not to be applied to medical exposures [2]. This approach has been adopted in all countries and, thus, dose limits are not applied to patients for justified procedures [12].

2.2.6. Non-medical procedures

Procedures involving exposure to ionizing radiation that may not yield direct health benefits for the exposed individual may be permitted or required by law in some jurisdictions [25–27]. Examples include, but are not limited to, imaging required for security purposes, purposes of crime detection or prevention, or medico-legal purposes of insurance companies or the courts. Examples of areas where exposures of this type may arise in paediatric radiology

include surveys of siblings in cases of suspected non-accidental injury, or age determination in court cases or migration tribunals.

The justification for such practices sometimes involves consideration of the public interest or the common good. Such practices are outside the scope of this Safety Report, but it is noted that the BSS set out requirements for justification and optimization for these practices [2].

2.2.7. Referral and/or appropriateness guidelines and clinical audit

A number of tools are available to facilitate identification of the correct radiological examination for a particular patient presentation. The most widely known involve "appropriateness or referral criteria and/or guidelines". Referral guidelines provide advice on the appropriateness of imaging modalities and specific examinations for many common clinical presentations. They also help exclude inappropriate examinations. In addition, the radiation dose and the strength of the evidence base for the advice offered are indicated. These guidelines need to be available to all clinicians who request imaging studies on children and adolescents.

An updated version of the referral guidelines for paediatric radiology published by the EC is reproduced in Appendix II [28, 29]. These guidelines and/or criteria and their application in practice are under revision and are further discussed in the justification sections of Sections 4–7. Further examples of guidance include the appropriateness criteria developed by the American College of Radiology in the United States of America, and the guidelines produced in the United Kingdom [30, 31]. There is much variability in the extent to which these tools are implemented in practice.

Tools of this type, or similar systems, are essential. In application, they provide an effective 'technology' that has recently been reviewed and has been shown to prevent inappropriate examinations and, thereby, reduce unnecessary radiation doses in adults [17]. They also show promise with younger patients, even though there is a dearth of studies in paediatric radiology [32]. Due to the value of such tools, the BSS require that relevant national or international referral guidelines be taken into account in the justification of a given radiological procedure for a given patient [2].

These tools have limitations in that they could be considered as advice and need not be given the status of a legal or required standard of practice. They need to be used with discretion in light of concrete situations, such as the immediately accessible technology and the condition, age and social circumstances of the patient. Regardless of the quality of the publicly available guidelines, there is a need for special consideration in paediatric radiology because of the different patterns of presentation and distribution of diseases.

There is widespread pressure to use radiological imaging techniques to screen for many diseases. In many cases, this form of health screening cannot be justified for unselected populations based on the overall risks and benefits involved. However, there may be considerable pressure from individual professionals and the public to undertake programmes of radiological imaging for health screening purposes.

While, to date, such pressures are not a feature of paediatric radiology, it is conceivable, given developments in the area, that they may arise in the future. If this is the case, then such a proposed health screening programme for paediatrics would need to be justified by the relevant health authority in conjunction with appropriate professional bodies [2]. This approach is similar to those already established for selected groups (e.g. mammography for women in certain age groups).

A neglected aspect of justification of medical exposures is the audit of its effectiveness. Recent developments in clinical audit of radiology have included approaches to audit of justification [17, 21, 33]. Referral and/or appropriateness guidelines can provide a useful benchmark for audit. Some audit studies with adults have demonstrated the potential for significant sustainable dose savings in the range of 20–50%. There is every reason to believe that such savings could also be achieved in paediatric radiology. Considerable future activity is anticipated in this area [17]. In a similar focus but strictly for radiation protection purposes, the BSS have a requirement that a radiological review be performed periodically, and this would include a critical review of the practical application of justification in the given facility [2].

2.3. OPTIMIZATION OF PROTECTION AND SAFETY

Once examinations are justified, they are required to be optimized (i.e. performed at a lower dose while maintaining efficacy and accuracy). Optimization of the examination has to be generic for the examination type and all of the equipment and procedures involved. It will also be specific for the individual, and include a review of whether or not it can be effectively done in a way that reduces the dose for the particular patient. For example, can a lower dose be used because less contrast or resolution is required, or because the patient is small, or can the irradiated volume be reduced?

Much of the material in Sections 4–7 can be viewed as contributing to the optimization process, including diagnostic reference levels (DRLs), dose constraints, good technique, good practice and optimized equipment subject to a regular quality assurance programme. Most of these areas need additional

attention in paediatric radiology as the available literature is, for the most part, based on radiology studies in adults.

Regulatory systems generally recognize that patients benefit from medical exposures. They essentially strike a bargain on behalf of society that dose limits will not be applied to justified medical exposures. This bargain places the burden of justification on the radiological medical practitioner and the referring practitioner [2, 5].

Medical exposure also includes exposures of individuals, such as members of the patient's family, who comfort or care for the patient during a medical exposure [12, 25]. This includes family members who help restrain a child during a procedure. The definition of medical exposure is also extended to include exposures that are incurred as part of a programme of authorized biomedical research.

2.3.1. Diagnostic reference levels

In the absence of dose limits, radiologists and other practitioners are often concerned to establish whether their practice is reasonable and whether they are achieving satisfactory examinations at reasonable dose levels. The adoption and use of paediatric protocols is paramount to achieving this goal in facilities in which children are imaged.

A tool for optimization is the concept of DRLs. These act as a trigger for review and are not intended to function as surrogate dose limits [12]. The BSS mandate their use [2]. In practice, they tend to be set so that if the values involved are exceeded, the radiological procedure involved needs to be investigated. This does not mean that there is necessarily anything wrong occurring, rather that there is something unusual which requires explanation, review and, possibly, a new approach. The DRL for an examination is generally derived from a regional or national survey of the doses for that examination. It is usually taken as the third quartile dose value for the dose distribution obtained in the survey, i.e. the dose value below which 75% of doses lie [34].

This may be illustrated by examining the EC's DRLs for 5 year old children in Table 2 [35]. These were established by surveying the doses received for a number of the more common projections in a range of institutions throughout the EU in the early to mid-1990s. For general radiography, various projections of chest, skull, abdomen, spine and pelvis are included. In practice, doses that were easy to measure, usually entrance surface dose (ESD), were taken. The terminology currently employed, with updated approaches to dosimetry, is slightly different but the numerical values are little changed [36].

As the DRL is taken as the third quartile dose value, there is a reasonable expectation that measurements averaged over a number of patients in any institution will lie below it. If the dose is systematically above the DRL, it is

relatively easy to identify problems, if any, and to correct them without loss of clinical information. For example, it might be the unnecessary use of a grid. It is also possible that the dose may be too low, and corrective action in this regard, in pursuit of necessary improvements in image quality, may also be warranted.

The values shown in Table 2 are from surveys conducted in 1996 and for 5 year olds. Different values might be obtained with newer technology, better techniques or newer dosimetry protocols, and with infants or 10 year olds. The values and units used in this publication are those employed in the publications cited. Some more up to date data for individual countries, involving newer equipment, and with older and younger age groups, are available (see Section 4.2.2 and Appendix III). Some of these are used as local departmental, regional or national reference values. However, more up to date EC or other international DRLs have not been adopted. This is a significant deficit in the support system necessary for optimization of protection and safety in paediatric radiology. Reference doses for other techniques are presented in the appropriate parts of Sections 4–7.

Finally, it is necessary to be aware that achieving dose levels below the DRL does not guarantee that optimization of protection and safety has been achieved. For example, one hospital in the United Kingdom has achieved local reference doses that are routinely 5–25 times less than the national DRLs. The hospital attributes this to careful optimization of all of the equipment and

TABLE 2. THE EUROPEAN COMMISSION'S DIAGNOSTIC REFERENCE LEVELS (STANDARD 5 YEAR OLDS) [35]

Radiograph	Entrance surface dose per image (μGy)
Chest PA	100
Chest AP (for non-cooperative patients)	100
Chest lateral	200
Chest AP (newborn)	80
Skull PA/AP	1500
Skull lateral	1000
Pelvis AP	900
Pelvis AP (infants)	200
Abdomen AP/PA (with vertical/horizontal beam)	1000

Note: AP: antero-posterior; PA: postero-anterior.

technique steps in the imaging process [37]. Thus, while DRLs are useful, they are not the only tool in the 'optimization toolbox' and the use of parallel approaches to implementing optimization needs to continue.

2.4. DOSE LIMITS AND DOSE CONSTRAINTS FOR OCCUPATIONALLY EXPOSED WORKERS, CARERS AND COMFORTERS, AND MEMBERS OF THE PUBLIC

Occupational exposure of radiation workers in hospitals or dental practices is treated in depth elsewhere and will not be addressed in detail here [2, 38]. Nevertheless, the dose limits for occupationally exposed workers and the dose limits for members of the public are provided in Table 3 [2]. In general, with good practice and good facilities, there will be no difficulty meeting the limits for workers, even for interventional procedures and special procedures (Section 5). However, in the absence of good practice or good facilities, there is some risk in these areas. Advice is provided that will help workers deal with these situations.

With regard to exposure of members of the public, this will not normally happen during paediatric radiology. Relatives or friends of the child will be classified as carers and comforters when they willingly and necessarily accompany, comfort, restrain or care for a child during a diagnostic procedure. Exposures received by them in these circumstances are classified as medical exposures and are not subject to the dose limits for public exposure [2, 5, 12, 39]. This arises because there is a direct benefit, both to the patients and to those who care for them.

Carers and comforters have to be provided with adequate information on how to protect themselves and, where necessary, with appropriate protective clothing and/or devices. Pregnant women are not to be allowed to assist in this

TABLE 3. DOSE LIMITS FOR OCCUPATIONALLY EXPOSED WORKERS AND FOR MEMBERS OF THE PUBLIC [2]

Type of limit	Occupational exposure	Public exposure
Effective dose	20 mSv per year	1 mSv per year
Annual equivalent dose to:		
Lens of the eye	20 mSv	15 mSv
Skin	500 mSv	50 mSv
Hands and feet	500 mSv	—

Note: Some flexibility with regard to averaging over longer periods is allowed [2].

way. The BSS [2] treat the selection of constraints for carers and comforters as a complex process in which it is required to take a number of factors into account, including the possibility that the individual carer or comforter is pregnant.

Dose constraints are a valuable planning tool in this context. They are used as an upper bound on the doses that individuals might expect to receive from a planned procedure, such as comforting, caring for or assisting with immobilization of a patient. An international consensus has not fully evolved on appropriate values, but those in Table 4 have been recommended by both the IAEA and the EC for those involved in a single episode of radio-iodine therapy [40–42]. These values are not to be rigidly applied as a dose limit. They may be exceeded where circumstances warrant it, for example, in the case of a particularly serious illness or difficult intervention [12, 41].

2.5. UNNECESSARY EXPOSURES

Unnecessary radiation exposures of patients can arise from failures of optimization or from errors. In paediatric radiology, these would include a radiological procedure performed on the wrong person, the wrong body part being subject to the exposure, the exposure being substantially greater than was intended, or, in the case of an adolescent girl, the inadvertent exposure of an embryo or foetus. Such events need to be investigated to determine the doses received and to determine and implement the corrective actions that are needed to prevent recurrence of the event. In some cases, such as for significant doses and as required under the law, the event would have to be reported to the regulatory body [43]. In all cases, the patient and the referring medical practitioner have to be informed [2].

TABLE 4. PROPOSED DOSE CONSTRAINTS FOR EXPOSURE FOR FAMILY AND CLOSE FRIENDS AS CARERS AND COMFORTERS [40, 41]

Age	Dose constraint (mSv)
Children (including unborn children)	1
Adults up to about 60 years old	3
Adults over 60 years old	15

2.6. SPECIAL CONSIDERATIONS ASSOCIATED WITH PREGNANCY

The general provisions of the BSS [2] and/or national legislation and professional codes of practice are required to be observed with respect to pregnant or potentially pregnant, occupationally exposed workers, and exposure of carers and comforters, and members of the public. These will not be repeated here and the reader is referred to the standard literature in this area [44–46].

Pregnancy can occur in adolescent girls. Precautions for this group have to be taken for exposures that may involve a foetus, and such exposures need to be avoided where possible. In female adolescents who are menstruating, the ten day rule needs to be considered when procedures with high exposures are involved, such as examinations or interventions involving the abdomen, pelvis or uterus, and in particular CT [45].

With this group, care and sensitivity have to be exercised with regard to the circumstances in which they are asked the relevant questions, so as both to respect their privacy and to increase the likelihood of being told the truth. With respect to pregnancy tests, many are of little value in excluding early pregnancy. In the EU, pregnancy is assumed in females of childbearing age in whom pregnancy cannot be explicitly excluded. If the requested examination is considered urgent, the referring clinician may override these concerns [45].

2.7. RESEARCH INVOLVING IRRADIATION OF CHILDREN

Biomedical research involving the use of ionizing radiation in children has to be performed within the well established framework provided by national and international recommendations [2, 5, 14]. This generally includes the provision that the research be approved by an ethics committee or institutional review board. The ethics committee or equivalent will generally include representatives of both institutional and public interests, who will consider the radiation benefits and risks associated with the use of radiation in the proposed research as just one part of their approval process. It is, therefore, essential that correct information on doses, risks and benefits, with respect to the proposed exposures, be presented to the ethics committee as part of the research proposal.

The use of repeated radiographs or CT scans to monitor progress in, for example, drug trials can only be undertaken after much deliberation. The examinations, where possible, have to be limited to essential scans or views. For example, yearly full skeletal survey examinations may not be necessary to monitor progress of therapies for Gaucher's disease. The use of dose constraints for exposures incurred as part of biomedical research is a practical means for radiation protection, and ethics committees need to specify such constraints in

granting their approval [2]. The detailed requirements are not addressed here but attention is drawn to the special issues involved in irradiation of children. Research is generally severely proscribed and is to be undertaken only when there is no alternative.

2.8. EDUCATION AND TRAINING

The need for medical practitioners providing radiological services, and for other professions, including medical physicists and medical radiation technologists, to undertake additional special education and training is well recognized and has been extensively discussed elsewhere [2–4, 12, 47, 48]. Formally recognized training in the radiological techniques involved and in radiation protection is required. Radiologists, medical physicists and medical radiation technologists working with children need to have specific training in the special issues that arise in paediatric radiology, over and above their general radiological training.

There is value in emphasizing the team approach to operational aspects of radiation protection and dose reduction programmes. Once such practitioners are trained, the need for continuing professional development in new techniques and technologies has to be recognized. The special needs for information and training of carers and comforters also have to be attended to in departmental training programmes.

Training material in support of the above areas and many of the objectives mentioned are available with free downloads of related presentations from the IAEA's Radiation Protection of Patients web site [20] and the Image Gently web site [10].

3. CONSIDERATIONS IN EQUIPMENT PROCUREMENT AND IMMOBILIZATION OF PATIENTS

Equipment used for paediatric radiology needs to be well designed and suited for the purpose. This is best ensured by having a good procurement policy that includes rigorous specification of what is required and verification that this is what the supplier delivers (see Section 3.1). In addition, a quality assurance programme is required to ensure that the equipment continues to be both functional and safe throughout its service life (see Section 3.2). This underlines the need to include medical physicists and quality assurance teams in procurement.

These considerations are important in paediatric radiology, where special steps are often necessary to ensure that exposure factors will be 'child-sized'. Where the same equipment is also used for adults, this can be a major problem. However, it can also be problematic even where equipment is solely for paediatric use. Equipment supplied with general purpose exposure protocols will inevitably and systematically overexpose children. Care in procurement also applies to ancillary items, for example, shielding for patients, lead aprons or protective screens. Special arrangements to facilitate immobilization of children are considered in Section 3.3.

3.1. EQUIPMENT PROCUREMENT

Radiological equipment can be very expensive. For this reason and to ensure safety, the procurement process followed has to be formalized [49]. It needs to specify the functions that the equipment is expected to perform. It is also important to ensure that equipment complies with appropriate international technical standards, such as those developed by the International Electrotechnical Commission (IEC) [50–54]. The safety standards of the IAEA will apply [2–4]. Such standards establish requirements for the levels of safety and of performance to be achieved. Taken together with manufacturers' specifications, these will ensure that the equipment purchased is appropriate, achieves the performance expected and is safe.

More attention needs to be given to the development of technical standards specifically for equipment intended for paediatric use. Examples of where this area has been neglected include automatic exposure control (AEC) systems in radiology and fluoroscopy, and the scanning protocols in CT. However, there are recent encouraging signs that both the industry and technical standards organizations recognize this and are open to suggestions for corrective actions. In

Europe, additional requirements are expected for all equipment, whether old or new, to meet minimum criteria of acceptability for use with patients [5, 49].

Once installed, equipment needs to be acceptance tested so that its supply, performance and safety are verified prior to commissioning for clinical use [49]. This is consistent with practice in some countries, where an agent (other than the supplier) who acts for the end user and/or the hospital has to sign off acceptance tests [5, 49]. Even where this is not legally required, it is important that it is done and properly documented. On installation, 'child-sized' exposure factors and protocols have to be established and communicated to all relevant staff as part of user training. This is particularly important with angiographic and CT systems [2, 49, 53–57].

The stages involved in the procurement process are listed in Table 5. All of these stages are important, regardless of the organizational framework in which they occur. Neglecting them almost inevitably leads to problems. The advice and support of an experienced procurement officer is invaluable. When estimating costs, the list in Table 6 may be considered. Where possible, these items need to be included in the main contract for provision of the equipment. Otherwise, many will be neglected and they are difficult to resource once the equipment has been delivered and paid for.

When second-hand equipment is considered, it needs to maintain the original manufacturer's specifications and meet the local minimum criteria for acceptability. Proof of compliance with these requirements has to be obtained. If an original feature is no longer functional but the equipment still meets the criteria for acceptability, this has to be clearly indicated in the documentation provided by the donor and/or seller [58].

In addition to the technical considerations, other operational, training and maintenance requirements have to be met. Satisfactory operator training is essential for all systems but particularly for CT, fluoroscopy and digital systems.

TABLE 5. STAGES OF THE PROCUREMENT PROCESS

Analysis of equipment requirements (clinical and technical)
Development of equipment specifications
Invitations to tender to appropriate suppliers
Analysis of tenders
Agreement of contract
Installation of equipment
Acceptance testing, commissioning and acceptability testing
On-site application training

TABLE 6. ITEMS TO BE INCLUDED IN THE COSTS OF A RADIOLOGY FACILITY

Purchase and installation of the radiology equipment
Building costs, including structural shielding
Provision of alternative services during refitting (where relevant)
Radiation protection devices, including the operator's protective lead screen, ceiling suspended lead screens, lead screens at the tableside, lead aprons, etc.
Ancillary equipment and/or accessories, including film processors, laser imagers, printers, cassettes, etc.
Test equipment for quality assurance
Ongoing running, maintenance, acceptance testing and quality control costs
Operator training and continuing education

The absence of such machine specific application training leads to systematic overdosing of patients and unnecessary exposure of staff over prolonged periods, sometimes several years. It is also important to budget for acceptance testing and ongoing quality control testing, particularly if this is to be carried out by third parties.

3.2. QUALITY ASSURANCE OF EQUIPMENT

A quality assurance programme in diagnostic imaging ensures quality during all phases of the operation of the service. One aspect of such programmes focuses on the operation of equipment. Quality assurance is required by the BSS, by many governments and the EC, and is recommended by numerous professional bodies [2, 49, 57, 59–61]. A quality assurance programme may be seen as part of clinical audit and part of the optimization process. It is important to ensure that equipment is working properly, is delivering the exposures expected and is compliant with good standards of installation and design.

Examples of relevant tests with a general radiography unit include checking whether the X ray beam is coincident with the light beam localization system, what its output is and whether the correct filters are present. Accurate, well adjusted collimation is essential in paediatric radiology because of the small size and close proximity of a child's organs. It is essential that the results from quality control assessments be integrated into the work of the management of the department, so that the findings are noted and acted on. A wide range of published guidelines are available for quality assurance [59–61].

3.3. CONSIDERATIONS IN IMMOBILIZATION

Immobilization is required with many children when performing radiographic studies. This is required so that:

— The beam can be correctly centred.
— Correct collimation can be obtained.
— Blurring and motion artefacts are reduced.
— The non-examined parts of the body are properly shielded.

Devices, such as sponges, sandbags or polymethyl-methacrylate plates, may be used with very small infants. In young children, it may be useful to take advantage of the period when the infant is calm or asleep after being fed to perform the radiological examination. With longer or more complex examinations, some sedation may prove valuable or necessary.

When assistance of a person is required for immobilization of or comforting a patient, this is, generally, not to be done by radiological or hospital staff. If, exceptionally, hospital personnel help in this way, the exposure they receive is considered an occupational exposure [2] and care has to be taken to ensure that the same staff members are not repeatedly exposed.

It is preferable that the patient be comforted or restrained by parents or relatives. In this case, the doses received are classified as doses to carers and comforters, and are dealt with as outlined in Section 2.4. This is the more appropriate route to follow as it avoids repeated exposure of the same hospital staff. It requires that the duties involved be undertaken by people who know the risks and that appropriate provision be made for informing them and protecting them (e.g. use of lead aprons). Those for whom pregnancy cannot be excluded will not be allowed to act as carers and comforters.

Even for young children, the time allocation for the examination has to include the time necessary to explain the procedure, not just to the accompanying parent or person but also to the child. Information specifically adapted for the parent and the child can be forwarded to the family in advance of the study. Video recordings or illustrated books and materials provided for viewing by children in the department in advance of the studies can also be helpful. Time taken to explain to a child and the parents what will happen is time well spent in obtaining optimal cooperation and securing a good examination [61].

4. GENERAL RADIOLOGY

The wide range of activities that constitute general radiology are considered in this section. They include film screen radiography, which was the staple of the field until recently. The subset of radiography practised with mobile equipment and the conditions under which it is appropriate to use such systems are also considered. Dental radiography is a special case and is briefly reviewed in Section 4.3. In all cases, radiography is now commonly practised using digital receptors to replace films and screens. The more widely used receptors in computed radiography (CR) and direct digital radiography (DR) are considered in Section 4.2.4. The section starts with a discussion of justification and the particular concerns it raises in paediatric radiology.

4.1. JUSTIFICATION IN FILM SCREEN RADIOGRAPHY, COMPUTED RADIOGRAPHY AND DIGITAL RADIOGRAPHY

As emphasized in Section 2.2, all radiographic examinations are required to be justified [2]. This gives rise to particular considerations in paediatric radiology. When doubt arises about whether or not a procedure is justified, the final decision will be made through consultation between the appropriately trained and/or experienced radiological medical practitioner and the referring medical practitioner, as appropriate. In this context, it is important to ask the referring practitioner, the patient and/or the family about previous procedures.

Examples of examinations which are often requested but which experienced paediatric radiologists will generally not advise as routinely indicated are listed in Table 7. In dealing with any request for an examination, it is important to consider the clinical history, previous examinations and the availability of alternative modalities that do not use ionizing radiation.

Excellent tools have been developed to assist in justification. They include referral or appropriateness guidelines for radiological examinations, such as those developed by various bodies [17, 28–30]. In these, a marker for the strength of the evidence base on which recommendations are made is provided. An updated version of the 2001 EC referral guidelines for paediatric radiology was published by the EC in 2008 and is reproduced in Appendix II [28, 29].

The guidelines are advisory rather than mandatory, and how they are applied may have evolved since their publication. They were developed for conditions that prevailed in Europe [62] at the time of publication and will need to be adapted to any specific circumstances to take due account of place and time. The issuing of a further revised set of guidelines is being planned by the EC.

TABLE 7. JUSTIFICATION PROCESS AND EXAMPLES OF EXAMINATIONS NOT ROUTINELY INDICATED

Justification
Justification is required for all radiographic studies.
The referring practitioner, patient and/or family need to be asked about previous procedures.
Referral guidelines need to be used where appropriate and available.
Alternative approaches, such as ultrasound or MRI, need to be used where appropriate.
Information needs to be provided to the patient in accordance with the BSS [2] or national standards.
Justification needs to be included in clinical audit.
Examples of examinations not routinely indicated
Skull radiograph in a child with epilepsy.
Skull radiograph in a child with headaches.
Sinus radiograph in a child, under 5 years of age, suspected of having sinusitis.
Cervical spine radiograph in a child with torticollis without trauma.
Radiographs of the opposite side for comparison in limb injury.
Abdominal radiographs in children with constipation.
Scaphoid radiographs in children under 6 years of age.

Similar recommendations are available in Canada, the United Kingdom, the USA and elsewhere, but can be difficult to access freely outside the professional bodies involved [15, 17, 30, 31]. There is much variability in the extent to which these tools are implemented in practice.

One of the more important ways of enhancing the justification process is through audit of referral patterns. In general radiology with adults, recent data suggest that 20–40% of examinations could be avoided if clinical decision guidelines were followed [63]. Use of guidelines has a significant impact on this, and with appropriate management, sustainable reductions in exposures can be achieved [5, 17, 33]. There is every reason to expect that guidelines and audit could be similarly effective in paediatric radiology. Thus, there is a compelling case for the wider use of both guidelines and audits.

For most purposes, the justification process followed for general radiography can be applied without much variation for CR and DR. The intent and outcome of the examinations is similar, and the major differences are variations in and the selectability of image quality and dose. These may need to be taken into account in the justification process in due course.

4.2. OPTIMIZATION AND GENERAL RADIOGRAPHY

4.2.1. Optimization in film screen radiography

Once exposures have been justified, protection and safety are required to be optimized [2]. A practical set of techniques for reduction of exposure and optimization of protection and safety in general paediatric radiography is provided in Table 8. This set is similar to the techniques used for radiography in general. However, there are special issues in paediatric radiology that need concerted attention.

One of these is the approach to manual exposure and AEC selection. In the late 1990s, 94% of exposures in paediatric radiography were performed using manual techniques, a much larger proportion than with adults [64]. This practice has to continue until such time as manufacturers provide AEC facilities and/or software based protocols for exposure that are appropriate for paediatric use. Currently installed AEC technology is generally not appropriate for children as the sensor size, geometry and software are normally designed or set up for adults.

Pending developments in design and in technical standards, it is, thus, preferable to use exposure charts specific to the radiographic technique, the patient's size and weight, and the presence or absence of a grid. Developments in exposure sensors and related software, and their intelligent application in paediatric radiology, are a significant challenge for the industry, standardization bodies and hospital staff. Considerable improvement could be achieved in this area with concerted cooperation.

It is important to have a standard type and number of projections for specific indications. Views in addition to the standard ones may only be performed on a case by case basis. For example, comparison radiographs in children for the assessment of trauma are not routinely necessary. It is also important, in practice, to consider the indication for the study. For example, in an intensive care setting, lines and catheters are inherently high contrast and there is significant opportunity for dose reduction when the clinical indication for a study is solely to confirm their position.

Beam output, filtration and focal spot size need to be known, to be appropriate for the application, and to be within acceptable limits [49, 59]. Doses can generally be reduced by using additional beam filtration and higher X ray tube voltage (kVp), but at some cost to contrast. Reliable, well managed film processing is essential. Use of fast film–screen combinations is possible for most radiography and allows a significant reduction in dose and exposure time [65]. The consequent reduction in resolution that is possible is insignificant for the majority of clinical indications.

TABLE 8. TECHNIQUES FOR REDUCTION OF EXPOSURE AND OPTIMIZATION OF PROTECTION AND SAFETY IN GENERAL RADIOGRAPHY

There needs to be a standard type and number of projections for specific indications.
Views in addition to standard may only be performed on a case by case basis.
Manual technique selection needs to be used pending equipment developments.
Where practical, a long (or the recommended) focal to skin distance needs to be used.
The X ray beam needs to be carefully collimated to the area of interest, excluding other regions, especially gonads, breast, thyroid and eyes.
Appropriate gonad, thyroid, ovary and breast shielding needs to be used.
Fast film screen combinations are acceptable for the majority of indications.
It needs to be ensured that film processing is working well.
An anti-scatter grid need not normally be used.
Postero-anterior projections need to be used, where practical, for radiographs of chest and spine.
It needs to be ensured that the correct filtration is used to reduce entrance surface dose.
As high an X ray tube voltage as is consistent with the examination requirements needs to be used.
Additional filtration at higher X ray tube voltage needs to be considered.
The use of a small focal spot size and short exposure times need to be balanced.
Quality assurance and audit programmes need to be used for all aspects of the department's work, including film processing.
A system needs to be introduced and used that allows patient dose to be assessed regularly.

Anti-scatter grids are normally not necessary because of the smaller size of children. Anti-scatter grids are usually not advisable for abdominal examinations in patients under 3 years of age or for skull radiographs on patients younger than 1 year old. Not using them avoids unnecessary exposure and results in an approximately 50% reduction in dose [65].

The use of postero-anterior projections, where possible, in performing radiographs of the chest and spine reduces breast dose but may not always be practical in smaller children who cannot fully cooperate. A system for periodic assessment of doses to the patient is needed, and this then enables comparisons to be made with relevant DRLs (see Section 4.2.2). This can become part of the system of quality assurance for medical exposures in the facility.

The beam has to be reliably collimated to the area of interest so that other regions are excluded. Accurate well adjusted collimation that is closely aligned with the light beam diaphragm is essential because of the small size and close proximity of a child's organs. In practice, it is not uncommon to see radiographs with wide open collimation. This practice is unacceptable and is a significant

contributor of avoidable doses. Additional shielding can be important for dose reduction. Gonad and breast shielding reduce the dose to these organs [66].

Each of these measures contributes systematic dose savings that often range from a factor of two to ten, with the result that their combined effect can dramatically reduce dose. Once good practice is established, it is important to sustain it through a quality assurance and constancy checking programme. This is particularly so for film processing. The advice on dose reduction presented here is based on that from the third 'ALARA' conference organized by the Society for Paediatric Radiology [67].

4.2.2. Doses and reference values for plain film radiography

A valuable tool in the optimization of protection and safety is comparison of the doses employed in a department with DRLs (see Section 2.3.1). The EC has proposed a set of DRLs for common radiographic projections (see Table 2).

These DRL values are for 5 year olds and different values would be obtained for older or younger children. However, it is felt that providing results for even one group may act as a marker for a department's performance. Some additional data for these older and younger age groups, from three EC paediatric trials conducted in 1989–1991, 1992 and 1994–1995, are presented in Table 9 but DRLs drawing on these have not been adopted to date [62]. However, the large ratio of the maximum to the minimum values seen ranges from about 30 to almost 100, and indicates the room available for improvement through optimization. DRLs are not dose limits but are, rather, intended as advisory action levels, which will trigger an investigation if exceeded (see Section 2.3.1).

Tables 2 [35] and 9 are taken from an EC publication of 1996. These tables are based upon practice prior to the heightened awareness of dosage in paediatric radiology and before CR and/or DR and exposure selection technology became dominant in some parts of the world. Hence, while they provide a useful upper bound, they need to be re-evaluated to take into account the developments in the past decade and a half.

In the meantime, most departments need to be able to achieve these levels. The United Kingdom Health Protection Agency reports that the dose at which reference levels might reasonably be set for adults have been reduced by a factor of at least two in general radiography since they started monitoring the area over two decades ago [68]. It is reasonable to assume that a similar level of attention to paediatric radiology might have a similar impact.

TABLE 9. VARIATIONS IN ENTRANCE SURFACE DOSE (μGy) IN EUROPEAN COMMISSION PAEDIATRIC TRIALS
(median, minimum–maximum values and corresponding ratio (minimum:maximum) [62])

Examination type	Infant			5 year old			10 year old		
	Median	Minimum–maximum	Minimum: maximum	Median	Minimum–maximum	Minimum: maximum	Median	Minimum–maximum	Minimum: maximum
Chest AP (1000 g newborn)	45	11–386	1:35						
Chest PA/AP	75	21–979	1:47	67	19–1347	1:71	71	17–1157	1:68
Chest AP (mobile)	90	34–718	1:21	68	29–333	1:11	91	29–760	1:26
Chest lateral				140	37–554	1:15	153	39–1976	1:51
Skull PA/AP	930	152–4514	1:30	967	242–4626	1:19	1036	130–5210	1:40
Skull lateral				703	138–2358	1:17	577	113–3787	1:33
Pelvis AP	260	18–1369	1:76	485	86–2785	1:32	812	89–4167	1:47
Full spine PA/AP	867	107–4351	1:41						
Thoracic spine AP							887	204–4312	1:21
Thoracic spine lateral							1629	303–6660	1:22
Lumbar spine AP							1146	131–5685	1:43
Lumbar spine lateral							2427	249–23 465	1:94
Abdomen AP/PA	440	77–3210	1:42	588	56–2917	1:52	729	148–3981	1:27

Note: AP: antero-posterior; PA: postero-anterior.

TABLE 10. ENTRANCE SURFACE DOSE PER RADIOGRAPH FOR DIFFERENT EXAMINATIONS AND AGES [1]

Examination	Age (a)	Mean entrance surface dose (μGy)
Abdomen AP	0	110
	1	340
	5	590
	10	860
	15	2010
Chest AP/PA	0	60
	1	80
	5	110
	10	70
	15	110
Pelvis AP	0	170
	1	350
	5	510
	10	650
	15	1300
Skull AP	1	600
	5	1250
Skull lateral	1	340
	5	580

Note: AP: antero-posterior; PA: postero-anterior.

Additional tables for the mean ESD for paediatric patients are provided for a limited number of projections in a range of age groups. The United Kingdom study (Table 10), also noted by UNSCEAR, is of value because it is more recent than the EC study [1]. The data from the Madrid study [69] are reported in Table 11 on CR and are cited in Section 4.2.4. The age cohorts and the projections are not exactly equivalent in the tables.

Notwithstanding this limitation, the data will be useful to those taking steps for optimization of protection and safety in their practice. A recent Bulgarian study compared the values with the EC DRLs where a large spread in values continues to be present [70]. The authors attribute this to a number of identifiable causes including widespread use of grids, use of low kVp values and, in some examinations, use of low speed film–screen combinations.

TABLE 11. COMPUTED RADIOGRAPHY MEDIAN ENTRANCE SURFACE DOSE FOR VARIOUS EXAMINATIONS AND AGE GROUPS [1]

Examination	Age range (a)	Sample size	Mean entrance surface dose (μGy)
Chest (no bucky)	0–1	1180	41
	1–5	309	34
	6–10	143	54
	11–15	92	10
Chest (bucky)	1–5	181	87
	6–10	255	105
	11–15	363	170
Abdomen	0–1	93	91
	1–5	30	225
	6–10	69	600
	10–15	150	1508
Pelvis	0–1	254	48
	1–5	128	314
	6–10	122	702
	11–15	137	1595

As noted in Section 2.3.1, DRLs may wrongly suggest that the optimization process is complete; continued attention to parallel means for optimization is necessary.

A survey from the EC SENTINEL Project of European paediatric doses in general radiography provides a wide range of information that is difficult to summarize, and some recommendations in respect of DRLs for both entrance doses and dose–area product values [71]. In the current international code of practice, dose–area product is now called kerma area product (KAP) [36]. This suggests that, in some countries, the aspiration to meet the EC DRLs is not being achieved. Additional data on these studies and others are presented in Appendix III. From the above, it is evident that there is a serious lack of current data for all forms of paediatric radiography in respect of one of the key markers for optimization, i.e. evidence based DRLs. It is essential that this be corrected.

4.2.3. Mobile radiography

Mobile radiography is valuable when it is impossible for the patient to come to the radiology department. However, it results in poorer quality images and can give rise to unnecessary exposures of staff and patients. For example, it is not

uncommon to find that inferior radiographs taken with a mobile unit need to be repeated on a fixed unit the next day, thereby increasing patient exposure. Thus, it is more difficult to warrant the use of mobile radiography when the alternative of a fixed unit is available. To minimize the problems involved, it is now widely accepted that, where practicable, X ray examinations need to be carried out with fixed units in an imaging department. Mobile units need to be used only for those who cannot safely be moved to such a fixed unit.

The principles outlined above for optimization in general radiography also need to be followed with mobile radiography, as far as it is practicable to do so. In addition, routine use may be made of portable lead shielding to protect nearby patients. The advice of the medical physicist and/or RPO needs to be obtained on how best to do this. For example, the risk may be minimal in an intensive care unit for newborns, where there is considerable space between the incubators. Tiny infants weighing as little as 500–600 g can be radiographed using very low exposure and there is very little scattered radiation.

4.2.4. Optimization with computed radiography and digital radiography

Film–screen radiography is now being superseded by a variety of digital technologies in many countries. In some western countries, this transition has been ongoing for over a decade and is now virtually complete. While several digital options are available, the most widely deployed are CR and DR, also sometimes known as direct DR [72, 73].

The most important distinction between the two is that CR involves an intermediate step in which the image is stored as a latent optical image, in a cassette-like device, before it is converted to electronic digital form, using laser technology. With DR, on the other hand, the image is created immediately in electronic digital form, in the image receptor. Images from both systems can be displayed on suitable high resolution monitors but in practice they are often printed out on film, particularly when resolution is a concern.

One of the driving forces in DR has been the possibility, indeed the promise, of significant dose reduction without loss of necessary image quality. The key factors in creating these possibilities include greatly improved contrast resolution, accompanied by almost infinite possibilities of processing the image after acquisition, with a view to improving the features eventually displayed. However, the improvement in image quality often results in higher patient dose, and the tendency to use higher patient doses than are necessary needs to be avoided [74].

Clinical and phantom studies have been performed by comparing radiation dose, image quality and diagnostic accuracy of film–screen and hard and soft copy digital chest radiography [75–78]. Using the EC (1996) quality criteria as a

semi-objective means of assessing image quality in chest radiography in children, Hufton et al. were able to demonstrate a dose benefit of 33% for CR compared with analogue chest radiography with a film speed of 400 [79]. Many other studies have also demonstrated potential benefits in terms of reduced dose with both CR and DR systems [72, 80, 81]. For example, a Spanish study found that an exposure reduction by a factor of 2.5 was consistent with images of sufficient quality to maintain the standards set by the EC [69, 82].

However, in spite of this success, a note of caution has to be raised. In general, digital imaging has the potential for dose reduction while improving image quality and diagnostic accuracy — but only with much attention to staff training and careful, continuous monitoring of departmental parameters and practices. The key issue is that, with image processing, the image quality will continue to look good even if the dose increases well beyond that required for an acceptable image. This removes one of the warning signs that, inadvertently, are provided by film–screen technology [83, 84]. On the other hand, with digital systems, dose cannot be reduced indefinitely as increased electronic noise reduces image quality. In practice, there is a tendency among technologists to avoid the need for repeats by erring on the side of overexposure [84].

Appropriate image processing is, therefore, crucial for optimization in producing a paediatric CR or DR image. To date, there is little standardization in the methods of image processing or their nomenclature. Practitioners are faced with the choice of accepting the supplier's default processing options or undertaking the arduous 'trial and error' task of customizing the processing for their local conditions.

In view of all of the above, it is important that radiology departments prepare well for the introduction of digital technology or for a new system involving digital technology. In the first instance, this needs to involve in-depth staff training on the specific system to be introduced. Generic training on digital systems, while helpful, is not adequate as there are significant operational differences between suppliers. Well trained staff need to adopt a team approach, in cooperation with the suppliers, technical staff, the hospital's medical physicist and maintenance staff, to identify and maintain suitable exposure parameters when a new digital system is installed. In addition, a good, practical, well integrated quality assurance programme is essential.

Exposure index (EI), which provides a method of monitoring dose, is an indicator of the radiation incident on the imaging plate, something which is essential. As illustrated in Table 12, different manufacturers have developed different indices [72]. Some of these can be confusing or misleading for end users as the index may be counter-intuitive (i.e. it increases when the dose required decreases).

TABLE 12. EXPOSURE INDICES FOR THREE MANUFACTURERS' DIGITAL SYSTEMS *(adapted from Ref. [72])*

Manufacturer	Exposure index	Unit	Mean receptor exposure		
			5 μGy	10 μGy	20 μGy
Agfa	lgM	bels	1.9	2.2	2.5
Fuji	S	No units	400	200	100
Kodak	EI	mbels	1700	2000	2300

By correlating ESD with the EI, a range of acceptable values for specific clinical indications for optimization can be obtained. Unfortunately, although the EI may appear on the image processing workstation and on hard copy radiographs, it may not transfer to the patient record and/or archive. The different forms of EI used and the problems of interconnection are standardization problems. Significant developments are being achieved in this area, and it is expected that there will be notable improvements in the next generation of equipment [85].

Further developments in equipment may also contribute to possibilities of dose reduction. These include development of completely innovative technologies, such as approaches based on slit scanning [86]. In a 2008 study, this system demonstrated very large dose reductions for skull, spine, pelvis and abdomen, and more modest gains for chest. However, it remains to be seen whether these are sustainable. Beyond these dramatic developments, most CR and DR manufacturers, recognizing that paediatric patients are different, have developed or are developing special provisions for paediatric examinations, including image processing.

In addition, it is essential that paediatric radiology undergo some standardization, and this requires commitment from end users, organizations setting technical standards and manufacturers. The importance of a continuous effort in this regard cannot be overemphasized, as it can lead to significant systemic dose reductions. The possibilities parallel the well established dose savings achieved by fast film–screen combinations in traditional radiology departments or dual readout CR technology, each of which, on the basis of a one-off initiative, can offer reductions in exposure in the range of 50% [87, 88]. However, while these possibilities are real, in practice there is a risk that patient doses will increase where digital technology continues to be introduced with inadequate preparation [89].

The recommendations given in Table 13 are designed to aid dose reduction and image management for optimization with DR and CR. The table relies on transfer of many of the practices that provide for good general

TABLE 13. DOSE REDUCTION FOR END USERS AND MANUFACTURERS OF COMPUTED RADIOGRAPHY AND DIGITAL RADIOGRAPHY EQUIPMENT

Dose reduction for end users
Justification is required for computed radiography and digital radiography studies as it is for general radiography.
Positioning, collimation and selection of exposure factors, etc. are as essential for optimization as in conventional radiography. A team approach to dose management is essential.
Team participants may include: a radiologist, medical physicist, medical radiation technologist, clinical engineer from the hospital; and a service engineer, application specialist and imaging scientist from the manufacturer.
Training of the radiologist and medical radiation technologist in the specific operational features of the computed radiography and digital radiography system in use is essential.
Dose reduction for manufacturers of computed radiography and digital radiography equipment
Manufacturers need to provide adequate end user training as part of the equipment supply package.
Nomenclature for digital imaging processing algorithms and exposure indices needs to be standardized.
Dose assessment is absolutely necessary for successful dose saving programmes. It is, thus, essential to standardize exposure indices.
It is essential to make provision for passing the information on exposures and doses from the radiological equipment to the picture archiving and communication system and/or the patient record in an accessible form [56, 81].
Dose measuring devices and dose indicators need to be calibrated and need to be protected from casual modification by the operator.
Manufacturers need to provide comprehensive training and guidance for the user on their version of exposure index or equivalent.
Manufacturers and organizations setting technical standards need to give particular attention to the special issues of paediatric radiology.

radiography, such as positioning, collimation, appropriate filtration and selection of suitable exposure factors (see Table 8). Recommendations directed to practitioners and the industry are included.

4.3. DENTAL RADIOGRAPHY

Much of intra-oral dental radiography, as in general radiography, involves capturing a two dimensional projected image of radiation distribution.

Furthermore, a wide range of digital facilities are now available for dental purposes although analogue film processing continues to be used. However, dental radiography normally involves a different group of professionals: dentists and dental assistants. It is addressed here briefly for completeness, and the reader is referred to the dental radiology literature for a fuller discussion [90].

4.3.1. Justification in dental radiography

Radiation protection in dental radiography, as with general radiography, begins with justification of the exposure. This may be seen as problematic where there is a tradition of routinely radiographing all patients. In addition, in dentistry, the referring medical practitioner and the radiological medical practitioner are frequently the same person. In other areas of practice, there is much criticism of this situation as it is regarded as leading to a form of 'self-referral' which results in systematic overutilization.

The absence of a tradition of well developed, evidence based guidelines for justification that have a high level of consensus among dentists is a further problem. Under normal circumstances, the risk from dental radiography is very low. Nevertheless, it is essential that all dental radiographic examinations have a clinical justification and show a net benefit to the patient. This is particularly true in the case of cephalometric radiography and orthopantomographic examinations. Table 14 summarizes guidelines that have been developed by the EC, and the following text also draws on this [90].

Obtaining bitewing radiographs for caries diagnosis needs to be based on a risk assessment. Intervals between subsequent bitewing examinations need to be reassessed on each occasion, as individuals move into and out of caries risk categories over time. In high caries risk children, there is good evidence to support taking posterior bitewing radiographs at the initial examination, even in the absence of clinically detectable decay. Where a child is classified as being at high caries risk, a subsequent bitewing examination may be made after six months. Radiographs ought not to be taken more frequently than this and it is important to reassess caries risk.

Evidence of no new or active lesions is an indication that the child has entered a moderate or low risk category. It is recommended that when children are designated as having moderate caries risk that they may have annual posterior bitewing radiographs. This may continue until no new or active lesions are apparent and the child has entered a low risk category. Radiographs for caries diagnosis in low caries risk children need to take into account the population prevalence of caries. Intervals of 12–18 months (deciduous dentition) and 24 months (permanent dentition) are appropriate, although longer intervals may be appropriate where the risk continues to be low.

TABLE 14. GUIDELINES TO FACILITATE JUSTIFICATION IN DENTAL RADIOGRAPHY [90]

All X ray examinations need to be justified on an individual basis. Anticipated benefits may include new information to aid patient management.
Referrals for radiography to hospitals or other dentists need to be accompanied by sufficient clinical information to permit the new practitioner taking clinical responsibility for justification of the examination.
No radiographs ought to be performed without obtaining a history and conducting a clinical examination.
Routine radiography of all patients in particular categories is unacceptable.
Obtaining bitewing radiographs for caries diagnosis needs to be based on a caries risk assessment.
Careful consideration needs to be given to the radiographic requirements for orthodontic treatment.
Careful consideration needs to be given to any requirement for cephalometric radiography.
Cross-sectional tomography and CT in children ought to be used rarely and only after rigorous justification with a view to answering specific clinical question(s).

When orthodontic treatment is required, most children are appropriately treated at approximately 12–13 years of age and require radiographs to confirm the presence and condition of all of the teeth. The radiographic examination will frequently include a panoramic or right and left oblique lateral radiographs. Upper anterior occlusal films are required to supplement the oblique lateral radiographs but not the panoramic study. Limiting the field size to the area required for diagnosis is important for panoramic radiography.

Cephalometric radiography may be required in very specific circumstances, such as to assess the third molar or the position of the lower incisors at the end of treatment with a functional appliance, and it needs to be performed only if the information is going to change the orthodontist's decision on treatment. Where possible, lateral cephalograms need to be collimated to limit the field to the area required for diagnosis.

Newer techniques, including CT based systems, are finding significant application in dental practice and are considered in the CT section (Section 6.4).

4.3.2. Optimization in dental radiography

The considerations already mentioned in Section 3 in connection with procurement, management and quality assurance for equipment hold, with appropriate adjustment, for dental radiography. The principal adjustments arise

from the fact that the equipment is less expensive, and that both the output and the workload are lower.

Notwithstanding this, significant accidents can and do happen even with new dental equipment [18]. The tradition of quality assurance is less well developed and protocols for some equipment types, such as orthopantomograms, need further work. In addition, there is a need for careful consideration of what may be achieved in remotely based quality assurance programmes, without sight of the equipment or the circumstances in which it is housed.

Practical advice usually offered for intra-oral dental radiography equipment is summarized in Table 15. Intra-oral DR offers a potential for further dose reduction, subject to the considerations raised in the section on CR and DR above. Additional literature on the quality assurance and performance levels necessary to ensure dose reduction with digital dental systems is, however, scarce.

In the absence of more fully developed paediatric guidelines, more detailed advice from adult practices will, for the present, have to be taken and suitably adapted for paediatric use from publications such as EC 136 [90]. However, the national reference dose of 1.5 mGy introduced in the United Kingdom for paediatric intra-oral radiography provides a useful benchmark [91]. DRLs of 60 mGy · mm for the dose–width product and 82 mGy/cm^2 for the KAP per radiograph for panoramic views are also recommended.

TABLE 15. GUIDELINES TO FACILITATE OPTIMIZATION OF PROTECTION AND SAFETY IN DENTAL RADIOGRAPHY [90]

Only equipment adequate to meet current standards is to be employed for paediatric dental radiography.
Optimal recommended X ray tube voltage for dental radiography is subject to some debate but 60–70 kVp is considered reasonable in terms of limiting entrance surface dose and general efficacy.
Short cone collimators ought not to be used.
Long collimators are an effective means of dose reduction and ought to be used.
Use of film holding devices may be considered.
Where use of film holders is not possible or practicable, rectangular collimation (which is now advised in both the United Kingdom and the USA) needs to be considered.
The fastest widely available films (F speed) will significantly reduce dose and ought to be used.
Intra-oral digital radiography offers the potential for further dose reduction; a reference dose of 1.5 mGy has been introduced in the United Kingdom.

It should be noted that there is a tradition in some areas of dental practice of providing protection over and above that which is strictly necessary, even where there is no evidence to require its use on technical grounds. For example, with good practice, there is no evidence of a requirement for gonad lead apron protection with general dental radiography. Lead shielding of the thyroid gland may be used in those cases where the thyroid is in the line of, or very close to, the primary beam. This advice is based on the assumption that good practice with good equipment prevails. Where this assumption might not be warranted, a good case can be made for continuing practices that may appear unduly cautious.

5. FLUOROSCOPY, FLUOROGRAPHY AND INTERVENTIONS

Fluoroscopic procedures may be classified into two broad types. Long established investigations, for example, gastrointestinal contrast studies, are considered in Section 5.1. Newer interventional and more sophisticated diagnostic procedures are addressed in Section 5.2. These often require higher doses and frequently involve using purpose designed equipment whose operational modes are not always clear to the end user. The risk of high doses to patients and staff is much greater with these procedures, although this risk is balanced by a therapeutic benefit. Increased awareness of the doses and risks from medical irradiation of children has led to the Image Gently Campaign [10]. Sections 5.3 and 5.4 deal with doses to patients and to staff.

The terms 'fluoroscopy' and 'fluorography' are not precise. 'Fluoroscopy' denotes procedures such as gastrointestinal studies involving contrast media, or other dynamic studies involving real-time visualization of macroscopic movement of anatomic and/or vascular structures using frame rates typical of those obtained in video systems. The dose rates used in fluoroscopy are categorized and regulated in many countries, with 'high' and 'low' doses allowed.

'Fluorography' denotes the capture of discrete images from an imaging chain and/or digital system, generally at lower frame rates and higher dose or dose rates than in fluoroscopy. For example, the frame rate might be 1 frame/s. The image quality is generally high and the images may be used for the final record. In cardiology, digital fluorography may replace cinefluorography at relatively high frame rates.

5.1. CONVENTIONAL FLUOROSCOPY

Safety issues for a range of techniques, such as micturating cystograms and gastrointestinal contrast studies, are treated in conventional fluoroscopy. These are generally well established techniques that are undertaken with well tested protocols and with equipment whose design and purpose are well accepted and understood.

5.1.1. Justification in conventional fluoroscopy

As with general radiography, it is required that all fluoroscopic examinations for infants and children be justified. The general points raised in

Sections 2 and 4 are repeated and summarized in Table 16. It is important to ask the referring practitioner, the patient and/or the family about previous procedures. Where doubt arises about the procedure, the final decision needs to be taken by an experienced radiological practitioner, where possible in consultation with the referring medical practitioner. Examples of examinations that are not routinely indicated[5] are also listed in Table 16.

At a more formal evidence based level, tools with a structured evidential approach which can assist the justification process are available. These include the referral guidelines developed by the EC, which are reproduced with permission in Appendix II [28, 29]. Other guidelines with a similar intent are also available [30, 31]. While these criteria are helpful, they are advisory and they were developed for conditions that prevail in Europe. They may need to be adapted to take account of changes in appropriateness with changes in place and time. In particular, the EC guidelines are a revision of a set originally developed in 2001 and issued in 2008, pending an update which is presently being considered. Notwithstanding this, they provide helpful advice on when it is appropriate to undertake an examination and what the alternatives are. As pointed

TABLE 16. JUSTIFICATION IN FLUOROSCOPY AND EXAMPLES OF EXAMINATIONS NOT ROUTINELY INDICATED

Justification
Justification is required for fluoroscopy studies.
The referring practitioner, patient and/or family need to be asked about previous procedures.
Referral guidelines need to be used where appropriate.
Alternative approaches, such as ultrasound or MRI, need to be used where appropriate.
Information needs to be provided to the patient in accordance with the BSS or national standards.
Justification needs to be included in clinical audit.
Examples of fluoroscopy examinations not routinely indicated
Upper gastrointestinal contrast studies of pyloric stenosis.
Upper gastrointestinal contrast studies of children with recurrent vomiting.
Contrast enema in a child with rectal bleeding.

[5] Endoscopy may be preferable to diagnose polyps; endoscopy or ultrasonography to diagnose inflammatory bowel disease; and nuclear medicine studies to diagnose Meckel's diverticulum.

out in Section 2, a good approach to justification is to audit the effectiveness of the process in practice.

Once an investigation has been justified, the path to follow will depend upon the clinical indication, and on the alternatives, such as ultrasound, CT, MRI, endoscopy, etc., that are realistically available in the time scale required. With this caveat, fluoroscopy continues to play a significant role in medical imaging. Micturating cystourethrography and gastrointestinal contrast studies, among other examinations, are regularly performed.

5.1.2. Optimization of protection and safety in conventional fluoroscopy

Once it has been decided to perform an examination, it has to be undertaken with a protocol that includes optimization for the specific equipment and facilities available, and for the requirements of the patient involved. Modern fluoroscopy systems tend to be provided with powerful ergonomically convenient software control systems. These allow exposures and full examination protocols to be pre-programmed, for both fluoroscopy and fluorography. In clinical practice, this can be a great strength but from a radiation protection perspective it may be problematic.

This can be so in particular if the pre-set protocols are for adults or larger children. Thus, it is essential to 'child-size' the protocols for the equipment in use [10, 20]. Within the category 'child-size', it is further necessary to differentiate protocols for children of differing ages and sizes. This cannot be assumed to have been done even in equipment supplied for paediatric use. Thus, it is essential to adopt the team approach to protocol development identified in Table 17.

The staff operating the systems need to be comprehensively trained in the systems' characteristics. Otherwise, these systems will result in exposures that vary over several orders of magnitude without the operator being aware of it. With such units, the traditional classification of fluoroscopic exposure levels as 'high' or 'low' becomes difficult to interpret or, on occasion, meaningless in practice, even though the regulatory framework surrounding these classifications continues to exist in some areas.

Participants in the team approach need to include a radiologist, medical radiation technologist, medical physicist and clinical engineer; and the service engineer and application specialist from the manufacturer. The team has to ensure compliance with local regulations and, perhaps even more importantly, it also has to ensure that those operating each system understand its features and the terminology used by the suppliers.

Training of the radiologist and medical radiation technologist in the operational features of each fluoroscopy and fluorography exposure system

TABLE 17. TRAINING FOR DOSE MANAGEMENT

A team approach to dose management in fluoroscopy is essential. Participants in the team include: a radiologist, medical physicist, medical radiation technologist, clinical engineer, company service engineer and company application specialist.
Training of the radiologist and medical radiation technologist in the specific operational features of each fluoroscopy system in use is essential.
Where non-radiologists (e.g. cardiologists or orthopaedic surgeons) are directly involved with the use of these systems, certified training needs to be provided for them within the national regulatory framework.
In larger departments, consideration needs to be given to training a trainer who will be fully conversant with the equipment and with how to introduce new or rotated staff to it.

employed is essential. In larger departments, consideration needs to be given to training a trainer who will be fully conversant with the equipment and with how to introduce new or rotating staff to it [92]. In some areas, consideration is being given to credential programmes that are machine specific. Such programmes already exist in other areas such as medical laser safety and with the training of airline pilots [93].

The examination technique is very important in optimization, and some guidelines are provided in Table 18. Table 19 provides useful additional information on dose levels at the entrance of the image receptor in different acquisition modes.

As with general radiology, positioning, collimation and selection of exposure factors are essential in optimization in fluoroscopy [94]. Coning to a small field of view can be achieved by the operator by using a light beam diaphragm, rather than fluoroscopy, for guidance; radiation-free adjustment of the primary and semi-transparent collimators may also be used if available. A low attenuation carbon fibre table may be used where possible; these are available from most fluoroscopic equipment manufacturers.

A removable anti-scatter grid needs to be available. This would normally only be used for older children (over 8 years of age) unless a younger child is particularly large. Such a grid may also need to be used in fluoroscopy for children where very high detail is required [62, 65]. Added copper filtration (e.g. 0.3 mm) can be used and can be left permanently in place if the equipment is used solely for children.

An overcouch tube may have significant advantages for general fluoroscopy in a paediatric department, provided that the operator is fully trained. This equipment configuration is less frightening for a child than that with an undercouch tube. It may slightly increase radiation dose but it makes access to the child easier for the operator and for carers and comforters, and it reduces the time required for the study. In operation, the distance between the tube and the image

TABLE 18. OPTIMIZATION IN CONVENTIONAL AND INTERVENTIONAL FLUOROSCOPIC TECHNIQUES

General applicability
Positioning, collimation, selection of exposure factors in optimization, etc. are essential in fluoroscopy.
The protocol needs to be 'child-sized', and the lowest dose protocol possible for patient size, frame rate and length of run needs to be used.
Fields need to be tightly aligned to the area of interest using the light beam diaphragm rather than fluoroscopy. The footswitch needs to be tapped to confirm position.
The image intensifier and/or receptor needs to be positioned over the area of interest before fluoroscopy is commenced rather than positioning during fluoroscopy.
Field overlap in different runs needs to be minimized.
Eyes, thyroid, breast and gonads need to be excluded whenever possible.
Use of electronic magnification needs to be minimized; digital zoom needs to be used whenever possible.
A low attenuation carbon fibre table needs to be used where possible.
A removable grid needs to be available, but is normally only to be used with older and large children (over 8 years of age).
Added copper filtration (e.g. 0.3 mm) needs to be used and can be left permanently in place if the equipment is deployed solely for children.
Pulsed fluoroscopy needs to be available and used where possible. Many workers recommend 3.5–7.5 pulses/s as adequate for guidance and/or monitoring of most procedures.
Static fluoroscopic or fluorographic images or the 'last image hold' facility need to be used to review the anatomy and/or findings.
An overcouch tube may be advantageous in paediatric radiology, provided that operators are fully trained to protect themselves from irradiation of the upper body, head and neck.
Fluoroscopy timing alerts need to be acknowledged during the procedure.
A calibrated kerma area product meter needs to be available and used effectively.
The dose needs to be recorded and reviewed.
Special emphasis on interventional fluoroscopy
The number and timing of acquisitions, contrast parameters, patient positioning and suspension of respiration need to be planned and communicated to the radiological and sedation team in advance to minimize unneeded runs. The plan needs to be communicated to the team members. Each run needs to be necessary for diagnosis or to assess progress and/or outcome.
Acquisition parameters need to be adjusted to achieve the lowest dose necessary to accomplish the procedure: the lowest dose protocol possible needs to be used, account being taken of patient size, frame rate and length of run.
The patient table needs to be kept as far from the X ray source as possible and the image intensifier and/or receptor needs to be as close to the patient as possible. The table needs to be moved away from the X ray tube in both planes. The patient needs to be moved as close as possible to the detector in both planes.
Fluoroscopy only needs to be used to evaluate a moving target or structure, and fluoroscopy time needs to be limited.

TABLE 19. ENTRANCE EXPOSURE RANGE AT THE IMAGE RECEPTOR IN TERMS OF AIR KERMA FOR VARIOUS ACQUISITION MODES

Operational mode	Air kerma range[a] (nGy/image)
'Low' fluoroscopy	6.0–8.5
'Medium' fluoroscopy	12–17
'High' fluoroscopy	24–34
Digital angiography	450–900
Digital subtraction angiography	4500–9000
Cardiac digital	90–130

[a] For a 23 cm image receptor, normal exposure rate, 30 pulses/s, 80 kVp and a standard total filtration of 2.5 mm Al.

intensifier needs to be maximized, with the table as low and as close as possible to the image intensifier [37].

With larger children and adolescents, the well known risks of these systems for the operators come into play owing to the increase in scattered radiation. This requires awareness on the part of the operators. In addition, it needs to be borne in mind that such systems are often designed and intended for use in the remote control mode, which generally allows the operator and attending staff to be in the protected console area. Obviously, this will not always be possible with small children, and the consequent risks to staff and to carers and comforters will require careful management.

Pulsed fluoroscopy can be effective in reducing dose, and it needs to be available and used where possible. It is a standard feature of modern equipment. Most fluoroscopy units have a range of 3–7.5 to 15–30 pulses/s. The lower range is satisfactory for many procedures and can be increased if the child is very mobile or uncooperative or if better detail is required.

Static fluoroscopic or fluorographic images may be reviewed from the digital or pulsed system (e.g. using last image hold) rather than from ongoing exposure. In addition, the duration of fluoroscopy and the number of images in digital runs need to be minimized with a view to dose reduction. Finally, it is worth noting that most doses to staff arise from radiation scattered from the patient, so that measures to reduce the dose to patients usually have a corresponding benefit in reducing doses to staff.

Fluoroscopy systems generally emit audible periodic time alerts. Acknowledging the cumulative timing device alerts may help in minimizing doses in the procedure.

A KAP meter is helpful in achieving knowledge of the dose used and is required by law in many countries [5, 93]. It is of value both for the patient record and as a training tool. A record of the information provided by the KAP needs to be transferred to the RIS/PACS systems. Ideally, future generations of equipment will be more flexible in this regard [50].

The KAP in fluoroscopic studies in children has to be kept as low as reasonably achievable, consistent with the diagnostic information required. However, the doses involved can be expected to vary depending on the age, sex, body mass, body thickness and cooperation of the child. The doses will also vary with the imaging objectives. Hiorns et al. have demonstrated that, for the eight most commonly performed fluoroscopic examinations, dose values which are a factor of between 5 and 25 less than the current national DRLs can be achieved [37] (see Section 5.3). The authors attribute this to improvements in both equipment performance and operator technique.

It is, therefore, recommended that paediatric fluoroscopy be conducted in specialist units whenever possible. When not possible, for example in non-specialist radiology departments with responsibility for paediatric imaging, the task may be assigned to a group of specially trained and experienced radiologists and medical radiation technologists (and other suitably trained professionals where appropriate, e.g. cardiologists).

5.2. DIAGNOSTIC AND THERAPEUTIC INTERVENTIONAL PROCEDURES

Interventional and more sophisticated diagnostic fluoroscopic procedures are generally conducted using purpose designed equipment that meets additional requirements, particularly in respect of real time monitoring of skin dose and/or dose rate [95]. The risk of high doses to patients and staff is much greater with these procedures. With care, however, both can be controlled, so that both operator and patient are not at unnecessary and/or undue risk. These procedures often provide a therapeutic benefit to the patient, and this needs to be included in the justification process.

Many of the measures that reduce doses to patients and staff in conventional fluoroscopy (described in Section 5.1.2) and the requirements set out in Tables 16–18 are also essential here. However, additional risk arises, such as the possibility of deterministic injury to the patient; thus, some points need extra emphasis, and additional precautions are required.

5.2.1. Justification in diagnostic and therapeutic interventional procedures

Interventional procedures in children are now more in demand, more sophisticated and take longer. Paediatric interventional procedures require individual justification and planning. This has to include a balancing of the risk against the therapeutic benefit. Such procedures, particularly for small infants, need to be undertaken by experienced paediatric interventional operators, both for clinical and for radiation protection reasons.

The procedure is to be performed only when absolutely necessary. As already mentioned (see Table 16), it is important to ask the referring practitioner, the patient and/or the family about previous procedures. Determination that the procedure is necessary relies on the judgement of the radiological practitioner and on its complexity. Referral guidelines for therapeutic interventions (even for adults) are not yet widely agreed upon [96–98].

With adults, there are wide variations in the numbers of therapeutic interventional procedures performed from country to country; even within one country, interregional variations in both numbers and complexity can be substantial. This partly reflects the general levels of socioeconomic provision but also reflects the level of staff training and the range of skills the individual practitioner has cultivated to a high level.

The provisions of Table 16 need to be followed, as far as possible, except for the recommendation about referral guidelines. The recommendations on audit and information provided to the patient need to be considered. In particular, it is now common to recommend that the patient be explicitly and fully informed in the case of interventions.

An IAEA study with the purpose of investigating the level of radiation protection of patients and staff during interventional procedures in 20 countries in Africa, Asia and Europe also included an analysis of the workload of paediatric interventional procedures [99]. Nearly 40% of the interventional rooms had an annual workload of more than 2000 patients in total. About 30% of participating countries have shown a 100% increase in workload in 3 years.

Analysis of the workload in participating centres indicated that most participating general hospitals perform paediatric procedures as well. The percentage of children in the total annual workload varies enormously between participating hospitals (0.2–35.4%). The number of paediatric patients compared with adults shows that in 2 countries the paediatric workload is in the range of 40–50% of adult procedures, 7 countries have 5–17%, and in the remaining 11 countries it is less than 5%.

The annual workload in dedicated paediatric hospitals in three countries was also variable, ranging from 240 to almost 4000 procedures per year. Of the procedures in paediatric hospitals, 2–36% are therapeutic procedures. However, it

is remarkable that the workload of paediatric interventional procedures can reach the levels of adult procedures even in developing countries. Special attention to dose is, therefore, required. It is essential to thoroughly investigate the level of radiation protection and the level of training in as many countries as possible, and in as many hospitals within each country as possible. This is necessary to evaluate the potential for improving the protection of children, given that for paediatric patients, risk of stochastic effects is the main issue [99].

5.2.2. Optimization of protection and safety in diagnostic and/or therapeutic interventional procedures

Complex interventional procedures can give rise to large doses to patients and staff, and have been shown to cause high peak skin doses in adults and high effective doses in children. The measures already specified in Table 18 will also contribute to reducing doses to patients in interventional work. Some additional considerations are listed in Table 19. The training and team issues already mentioned in Section 5.1 (see Table 17) are also essential here. It is well recognized that operator training improves performance with interventional procedures conducted on adults [96].

Likewise, in paediatric interventions, it has been demonstrated, in a study involving over 1000 procedures, that specific training improves the use of safety measures. This included use of hanging lead shields and lead eye glasses. Training reduced imaging time and KAP significantly for relatively uncomplicated procedures but was not as effective in bringing about change for complicated ones [92].

Complex procedures need to be pre-planned, and what is expected to be involved needs to be communicated to the team. For example, the number and timing of acquisitions, contrast parameters, patient positioning, suspension of respiration and sedation needs to be planned in advance, to the extent possible, to minimize improper or unneeded runs. The acquisition parameters need to be selected to achieve the lowest dose necessary to accomplish the procedure, with account taken of the dose protocol, patient size, frame rate, magnification and length of run. During the procedure, the operator has to ‘step lightly’ on the fluoroscopy pedal [10].

The table needs to be moved away from the X ray tube in both planes to maximize the distance between the source and the patient. The distance will generally be greater than 37.5 cm [10]. The image intensifier (or flat panel detector) needs to be as close to the patient as possible, to minimize patient to detector distance, while allowing room for manipulation of needles, wires and catheters. These considerations apply to all projections: vertical, lateral and oblique.

Image acquisition using fluorography or during digital subtraction angiography accounts for the largest radiation doses during many interventional procedures [100, 101]. Exposure factors for fluorographic image acquisitions and quasi-cine runs are much higher than those for fluoroscopy. The acquisition mode needs to be carefully selected as dose rates involved can be up to a couple of orders of magnitude higher than for fluoroscopy [102, 103].

When C-arm RIS equipment is used, the proximity of the skin to the X ray source in lateral and oblique views might be closer than during the PA view, and may result in an increase in skin dose. After the tube is placed in the lateral position, the patient needs to be distanced from the source to the maximum extent allowed by the equipment. In attending to this, the dose readout systems that are a feature of interventional equipment need to be consistently employed by the operator as part of their active monitoring of the procedure [50, 95]. The cumulative readouts from these systems need to communicate readily with the PACS and RIS systems.

Paediatric interventional procedures have unique features related to patient size. Patient sizes vary in practice, from as small as 450 g to in excess of 100 kg. To gain access to the small child, it is often necessary for the interventionist to come close to or, on occasion, enter the beam. 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. They might also enter the beam urgently when an unexpected event or a complication occurs.

It is well known that with heavier children the indicators for patient dose increase [104]. However, it is further recognized that children are not small adults [105]. As mentioned above, imaging equipment needs to be specifically designed for use with children and the operators need to be trained accordingly. The generator needs to provide a large dynamic range of current (mA) and tube output index for defined kV (the product of tube current and time (mAs)) to minimize the range of kVp and the exposure time needed to compensate for differences in thickness. It is also desirable for there to be three focal spots, a lateral imaging plane, spatial and spectral beam profiling, and a well functioning system of entrance exposure regulation. Strauss recommends the entrance exposure values at the image receptor listed in Table 19 [105]. He also provides suggestions with regard to how these values can be adapted to other operating conditions.

Another unique feature in paediatric intervention is the large size of image intensifiers or digital image receptors relative to an infant's size. With infants and small children, the image intensifier will completely cover the patient. In such situations, the accuracy of collimation is more important than for adults, where the field of view is often allowed to fill the image receptor field. This is unacceptable in paediatric cases. Thus, ensuring that the collimation is precisely

aligned becomes a key design, performance and quality assurance issue. There is also an increased need to use magnification in children. This can further increase dose when analogue magnification is unnecessarily used [100].

After the procedure, the dose records may be noted and reviewed. A dose record may be included in the medical record [50, 95]. The 'step lightly' campaign recommends audit of radiation doses for all operators [10]. Specific feedback and additional training need to be provided where necessary [20, 21].

Implementing the above measures needs to be balanced against safe, accurate and effective completion of the procedure. Not all of the steps mentioned may be possible in each case, depending on patient size, the technical challenge and the critical nature of the procedure. The goal is to minimize the dose to the patient while providing important and necessary medical care.

5.3. DOSES TO PAEDIATRIC PATIENTS AND REFERENCE LEVELS FOR FLUOROSCOPY AND INTERVENTIONAL PROCEDURES

Only limited data are available for reference dose levels for both fluoroscopic and interventional paediatric procedures. The available data are not completely satisfactory as they are dependent on the generation of the technology on which they were measured.

Three sets of data available for fluoroscopy from the United Kingdom are illustrated in Table 20. The third column from the left provides the current national reference doses for paediatric fluoroscopy (2005 review) [89]. The column to its right provides the set of national reference doses that prevailed in the 2000 United Kingdom review [106]. Clearly, the reference doses were reduced in 2005 in all cases except one, the barium swallow at 10 years of age. This demonstrates the value of an ongoing national programme of monitoring and of hospital involvement and/or collaboration in this area.

The reduction observed is consistent with the pattern reported by the Health Protection Agency for other examinations in adults. It may also be noted that the reference doses are set at the third quartile level, which means that 75% of those involved achieve lower values. Additional data to this effect are provided in the United Kingdom reports [89, 106].

The right hand column of Table 20 lists local DRLs established at Great Ormond Street Hospital, London [37]. Hiorns et al. have also demonstrated that, with the eight most commonly performed examinations (2215 cases), the KAPs (75th percentile) for upper gastrointestinal studies and micturating cystograms are substantially lower (by a factor of between 5 and 25) than the current national doses. Some of the median values are 50 times lower. Their small KAP values in all examinations demonstrate the substantial reduction in dose and, consequently,

TABLE 20. COMPARISON OF THE UNITED KINGDOM'S REFERENCE DOSES (2005 AND 2000) FOR PAEDIATRICS AND DIAGNOSTIC REFERENCE LEVELS AT GREAT ORMOND STREET HOSPITAL [37, 89, 106]

Examination	Age (a)	2005 national reference doses (cGy · cm^2)	2000 review kerma area product per exam (cGy · cm^2)	Great Ormond Street Hospital diagnostic reference level (cGy · cm^2)
Micturating cystourethrogram	0	30	40	5
	1	70	100	5
	5	80	100	10
	10	150	210	42
	15	250	470	42
Barium meal	0	40	70	8
	1	110	200	8
	5	130	200	12
	10	240	450	32
	15	640	720	32
Barium swallow	0	40	80	8
	1	120	150	8
	5	130	150	12
	10	290	270	32
	15	350	460	32

in risk that can be achieved when both equipment performance and operator technique are optimized.

While different institutions will have differing practices, it is important that practitioners be aware of the range of KAPs achievable and of the fact that national or international DRLs do not necessarily represent best practice, and may in fact be falsely reassuring. The Great Ormond Street Hospital values are a compelling example of what can be achieved with a dedicated approach [34]. The figures in the table also illustrate the spread in values that arises, and are a reminder of the need for much more work in the area. Other studies confirm that large dose savings can be achieved with relatively straightforward technical strategies [107]. The results of a limited European survey are available and have been published [71]. Some details are provided in Appendix III.

With regard to interventional radiology and cardiology, there has been a significant growth in the literature available worldwide in the past decade. Studies are now available for adults in respect of reference values, the mean dose per procedure and local DRLs [31]. While these techniques are now commonly used in paediatric radiology, few studies are available detailing the doses or frequencies involved.

However, Onnash et al. report mean effective doses and KAP normalized to body weight in interventional cardiac procedures as illustrated in Table 21 [1, 108]. This may prove to be a useful approach from the point of view of paediatric radiology. It may, with some care, be used to draw on adult studies pending a larger range of paediatric data becoming available [108].

Deterministic injuries following interventional procedures that have been reported in adults, and their time course and/or dose relationship, are presented in Table 22 [109]. They include serious injury to skin and underlying tissues, although these are less likely in children than in adults. Many of these injuries may be missed as they become manifest after the patient has left hospital and/or the team caring for the patient may not be aware of the risk of radiation injury [100].

To help avoid these injuries, modern interventional equipment generally provides a dose estimate at the interventional reference point. The IEC defines the interventional reference point as 15 cm from the isocentre towards the X ray tube [50, 95]. The interventional reference point is related to the dose to the skin. Where it is suspected that a patient has received a high skin dose (2 Gy or more), a follow-up visit 30 days after the procedure has to be planned. The parents and/or the patient have to be informed that if symptoms of skin injury (i.e. skin

TABLE 21. EFFECTIVE DOSE AND MEAN KERMA AREA PRODUCT PER KILOGRAM FOR A SELECTION OF PAEDIATRIC CARDIAC INTERVENTIONS *(based on Ref. [108])*

Procedure	Number	Mean kerma area product ($Gy \cdot cm^2 \cdot kg^{-1}$)	Effective dose (mSv)
Atrial septal defect occlusion	259	0.42	3.9
Patent ductus arteriosus occlusion	165	0.35	3.2
Balloon dilatation	122	0.48	4.4
Coil embolization	33	0.50	4.6
Ventricular septal defect occlusion	32	1.3	12
Atrial septostomy	25	0.39	3.6
Patent foramen ovale occlusion	21	0.23	2.2

TABLE 22. DOSE, TIME AND DETERMINISTIC INJURIES [109]

Peak skin dose band	Range (Gy)	Prompt: <14 d	Early: 14–40 d	Mid-term: 40–400 d	Late: >400 d
A1	<2	No effects expected			
A2	2–5	Transient erythema	Transient hair thinning	Hair recovery	None expected
B	5–10	Transient erythema	Erythema, epilation	Recovery; at higher doses, prolonged erythema, permanent epilation	Recovery; skin changes at higher doses
C	10–15	Transient erythema	Erythema, epilation, possible dry or moist desquamation	Prolonged erythema, permanent total epilation	Telangiectasia, induration; skin likely to be weak
D	>15	Transient erythema with possible pain; oedema and acute ulceration at very high dose	Erythema, epilation, moist desquamation	Dermal atrophy, secondary ulceration, dermal necrosis	Dermal atrophy, induration, late skin breakdown; persistent wound; surgical intervention likely

irritation or reddening) occur, these have to be reported to the department in which the procedure was performed.

5.4. DOSES TO STAFF IN FLUOROSCOPY, INCLUDING INTERVENTIONAL FLUOROSCOPY

The team approach already mentioned needs to be adopted for management of staff doses. All team members need to be aware of the radiation exposure issues with fluoroscopy and interventional procedures, and the means of controlling them. In practice, those operationally involved need to be recognized radiological medical practitioners and medical radiation technologists — i.e. they have the requisite specialist education and training, including in radiation protection. This may mean, as is required in many countries, that they need to undergo special training in the techniques involved and in radiation protection [47, 100].

The requirements for good practice have much in common with the practice for adults but are adapted for paediatric radiology. The main features are presented here for ease of reference. Exposure of staff can arise from the direct beam or from scatter from the patient. For a well designed set up with good protocols, there will be little risk of exposure to the direct beam, with the exception of those circumstances where the operator's hands may, for exceptional reasons, be in the beam for short periods (see below). This apart, most exposure of staff, in practice, arises from scattered radiation.

It is widely recognized that for a given set-up, doses to both patients and staff are dependent on the total amount of X ray energy emitted from the tube. The connection between doses to staff and doses to patients also arises from the fact that most exposure of staff is due to scattering of radiation from the patient. Vano et al. have demonstrated a linear relationship between KAP to the patient and staff doses in cardiac simulations [110, 111].

Thus, minimizing exposure of staff will be facilitated by optimization for the patient. Many researchers have demonstrated that the exposure regime and/or protocol employed is very important in determining doses to staff. For example, in digital fluoroscopy, cine, digital 'cine-like' or digital subtraction angiography runs, the dose to staff due to scattering of radiation from the patient can be several orders of magnitude higher than during fluoroscopy [110–113].

Doses to staff are also dependent on the size of the patient, which influences the amount of scatter. The amount of scatter is also influenced by the complexity of the procedure and by the adequacy of the training and experience of the operating staff [92, 95]. Simulation studies by Vano et al. have demonstrated that the dose to staff due to scattering of radiation from larger children is likely to be higher by a factor of up to 20–30 than that due to scattering from infants [110].

To reduce exposure to scattered radiation, staff need to position themselves strategically with respect to the configuration of the image receptor and the X ray source assembly (Table 23). The operator generally needs to be on the image receptor side and, where possible, to step back during injections. The dominant direction for scatter tends to be from the patient backwards towards the X ray tube. This is well illustrated in Balter's diagrams [111], which are reproduced in Appendix IV.

Operators need to become familiar with the profile of scattered radiation in the room when the tube is oriented in the main directions used in practice. Where equipment has been designed and sold for interventional use, the suppliers, in compliance with international technical standards [114], have to provide isodose curves such as those shown in Appendix IV [47, 92]. The room floor could be colour coded to help staff position themselves in such a way as to minimize exposure. While Balter's data are based on adults, they provide some guidance

for paediatric interventionists, pending the availability of more complete paediatric data [110, 111].

During interventional procedures, the staff member most at risk is the operator. Others need be in the room only if their presence is required. All need to have adequate personal protection, such as good, well designed lead aprons, thyroid collars and lead glasses, as required. Where paediatric interventionists performing these procedures spend much of their working life wearing lead aprons, the risk of back or joint injury needs to be considered.

Two-piece aprons are available which redistribute the weight so that it is not all carried on the shoulders. Wrap-around aprons are also now available in which the shielding is biased towards the front, where the risk of exposure is higher for most of those involved. Leaded thyroid collars and/or lead glasses (prescription and non-prescription are available) with side shielding need to be worn in view of increasing concerns about occupational exposure [115].

Radioprotective gloves can attenuate scatter by about 50% but can be counterproductive if inadvertently placed in the beam, as they may interfere with the AEC and increase exposure. They also reduce dexterity and speed, hinder the work and can give a false sense of security. If, exceptionally, hands need to be placed in the beam, they ought, if possible, not to be placed between the X ray tube and the patient. Foot and leg doses to the operator can be significant and are receiving increasing attention as procedures become more complex and longer. Lead skirts for the table or drapes of newer compound material can reduce the scatter of radiation to the legs and ankles by as much as 10- to 20-fold [111, 116]. It is now possible to obtain single use drapes for scatter reduction.

In a study of adults, use of a power injector instead of hand injecting contrast material has been shown to be a highly effective way of reducing operator dose during angiography [117]. While the reductions may not be quite as dramatic in paediatric radiology, injectors need to be used where possible. In addition, the operator needs to step away from the image intensifier and/or behind a mobile lead screen during contrast injections. When manual injection is necessary, the distance from the patient needs to be maximized by using a long catheter.

Occupational dose measurements have to include readings from at least one dosimeter under the lead apron to assess whole body dose. Additional dosimeters over the apron to evaluate thyroid, hand and arm, and eye doses are advisable in some situations. For example, the ICRP recommends two dosimeter badges for interventional work, one under the apron and one on the shoulder over the apron. The second dosimeter is sometimes taken as being indicative of doses to areas such as the eyes, head, neck and even thyroid, and both are used in estimating effective dose [118]. Slight angulation of the beam away from the hands, strict collimation and careful attention to finger positioning will help to reduce exposure of the operator.

TABLE 23. REDUCING DOSES TO STAFF IN INTERVENTIONAL FLUOROSCOPY

Only those necessary for conduct of the procedure are to be in the room.
Personnel needs to be moved away from the table, preferably behind protective shields during acquisitions.
The operator needs to stand to the side of the image intensifier.
The operator (and other team members) may step back during injections.
The operator needs to use a power injector and to step back from the image intensifier and/or behind a mobile lead screen during contrast injections.
If manual injection is necessary, the distance needs to be maximized using a long catheter.
Doses in the room and from undercouch tubes can be greatly reduced by well configured and properly used tableside drapes.
Movable overhead shields need to be used for face and neck protection. These need to be positioned prior to the procedure.
Well designed suspended shielding and/or viewing systems are helpful to operators who learn to become skilful in their use.
Suitable, well fitted radioprotective aprons of appropriate weight need to be worn.
Aprons need to be well fitted, with arm wings to protect the axillary tail for females.
A thyroid collar and/or lead glasses with side shielding need to be worn.
The operator and personnel need to keep their hands out of the beam.
When, exceptionally, hands need to be placed in the beam, they ought, if possible, not to be placed between the X ray tube and the patient.
Radioprotective gloves may be worn where appropriate, but they can be counterproductive, reduce flexibility and dexterity, and interfere with the automatic exposure control.
Slight angulation of the beam off the hands, strict collimation and careful attention to finger positioning will help to reduce exposure of the operator.
Occupational dose measurements need to include at least one dosimeter badge under the lead apron to assess whole body dose.
Additional dosimeter badges over the apron to evaluate thyroid, hand and arm, and eye doses are advisable in some situations.

With large KAPs and work in which the operator, for effectiveness, needs to remain close to the patient, the risk of high doses to the head and neck of the operator from scattered radiation will arise. In this context, any gain from the small size of the patient may be offset by the closeness of the operator and/or the complexity of and the dexterity necessary for the manipulation involved in the procedure. This can often be the case in paediatric interventional cardiology.

In studies [110, 115], Vano et al. have drawn attention to the risk of damage to the eyes of the operator and estimate that the eye dose will be about 7 $\mu Sv \cdot Gy^{-1} \cdot cm^{-2}$ of KAP to the patient. Table 23 provides a summary of many of the key points discussed above. For maximum impact, it is essential that the advice of the medical physicist and/or RPO be obtained to allow local protocols and the physical environment to be considered in the optimization of protection and safety for staff.

6. COMPUTED TOMOGRAPHY

In developed countries, over 10% of diagnostic radiological procedures are CT examinations. In the USA, the total number of CT examinations per year for all age groups is about 60 million, of which 7 million are paediatric [1, 10]. Paediatric CT is a valuable imaging tool, the use of which has been increasing at a rate of about 10% per year recently. An eightfold increase has occurred over the past 20–30 years [7, 10]. The rate of increase in examination numbers may be even greater in special cases.

Given the evidence of CT (over)utilization in recent years, in particular in the USA, there are organized efforts to increase radiation awareness and promote safety in paediatric imaging [10, 119]. Availability of alternative imaging modalities that do not require the use of ionizing radiation and careful review of body CT requests in US paediatric hospitals contributed to a significant decrease of CT utilization in 2006 and 2007 [119]. Some authors believe that many of these examinations may not be necessary or justified (see Section 6.1). The dose for each individual examination is relatively high. CT is not the most frequent examination but it contributes the largest component of the collective dose from medicine, 50–67% in some US tertiary referral centres [120–122].

While the situation in paediatric CT is not fully documented, it has led to increasing concern about the exposure of children, particularly as adult scan settings were used in paediatric CT for many years. Consequently, much comment and advisory material addressing the area has been developed. This includes that from the US Food and Drug Administration, the US National Cancer Institute (NCI), the National Council for Radiation Protection, and the increasingly visible Image Gently Campaign, in addition to that from professional bodies [7, 10, 20, 123].

6.1. JUSTIFICATION IN COMPUTED TOMOGRAPHY

The references in the previous section generally include advice that paediatric CT has to be justified. This is not surprising as some authors have estimated that between a third and half of the examinations occurring may not be necessary, and many are conducted using inappropriate technical factors [32, 124]. At the extreme, Oikarinen et al. [32] report that 77% of lumbar spine examinations in their study of a population under 30 years of age were not justified.

This issue has also been given added impetus by a growing active press and media interest in the area, since about 2007. Government and professional bodies

in the USA now have a consistent response which includes justification [7, 10, 15, 17, 123]. Some specific approaches would have an immediate impact in reducing paediatric doses. Examples are summarized from these and other sources in Table 24. While many of these are generic, they are included here as they are necessary when planning an operational response and for ease of reference and/or completeness.

It is required that each CT examination be rigorously justified. In this regard, tools such as the evidence based referral guidelines mentioned earlier are helpful, and those published by the EC are reproduced in Appendix II with the caveats already noted (see Sections 2, 4 and 5) [27–31]. Some workers have developed or added local guidelines or referral protocols. These are helpful where they are well understood and well incorporated into a local practice [9]. For example, Broder discusses the value of rules and guidelines in limiting CT overutilization in the emergency room setting [125]. The following paragraphs

TABLE 24. IMMEDIATE STEPS TO REDUCE PAEDIATRIC COMPUTED TOMOGRAPHY DOSES [7, 9, 123]

Immediate steps to reduce paediatric CT doses
CT examination is required to be rigorously justified and inappropriate referrals eliminated.
Only necessary CT examinations are to be performed.
The number of multiple scans with contrast material needs to be reduced.
The referring practitioner, patient and/or family needs to be asked about previous procedures.
Referral guidelines need to be used where appropriate.
Alternative approaches, such as ultrasound or MRI, need to be used where appropriate.
Information needs to be provided to the patient in accordance with the BSS or national standards.
Justification needs to be included in clinical audit.
Some specific measures to assist with these objectives
Age specific pathology and its prognosis need to be respected.
Individual paediatric questions need to be respected.
The potential contribution of the scan to patient management and outcome needs to be considered.
The patient's record and previous radiology examinations need to be considered.
Cost and radiation exposure need to be respected.
CT needs to be replaced by an examination with no or with lower radiation exposure (e.g. ultrasound or MRI).
The follow-up examination needs to be delayed unless a decision based on the scan is needed at the time.

will be helpful in establishing local guidelines and/or in practically implementing those from the literature.

Special attention is needed for age specific pathology, its prognosis, individual paediatric questions, the costs and the radiation exposure involved in an examination. Previous examinations are required to be considered [2], and their consideration is implied by the proposed IAEA Smart Card project and the Image Gently Campaign [10, 20]. This may render the procedure under consideration unnecessary or allow it to be replaced by a less dose intensive one. Likewise, the potential contribution of the scan to the management and outcome of the patient's condition needs to be considered. Follow-up examinations need to be delayed unless therapeutic decisions based on them are needed immediately.

CT examinations need to be replaced, where appropriate, by others without radiation or with lower exposure (e.g. ultrasound, MRI or conventional radiography). In children, ultrasonography has to be the first line imaging study of the abdomen since their slim body habitus allows access even to the deeper abdominal structures. In experienced hands, ultrasonography can provide substantial clinical information and may obviate the need for CT.

Ultrasonography has to be the examination of choice in children suspected of acute appendicitis. CT need not be performed without a preceding clinical examination by an experienced surgeon. When ultrasonography and radiography are unlikely to provide the answer, the choice of examination is often between CT and MRI. The severity of the suspected disease, the study duration, radiation exposure, side effects of anaesthesia and contrast agents, and specific information required all need to be evaluated.

Problems requiring detailed information on soft tissues, the nervous system or bone marrow are often best evaluated, in the first instance, with MRI. A large body volume, time and anaesthetic restrictions under emergency conditions, such as multiple trauma or the need for information about cortical bone, favour CT. Malignant disease with a poor prognosis renders the potential detriment from radiation exposure less important. Where there is a probability of curative treatment, the added risk of many follow-up studies during and after treatment has to be carefully assessed.

In all of these circumstances, it is important to reduce the number of multiple scans with contrast material. Often, CT scans are done before, during and after intravenous contrast injections. Radiation exposure may be reduced by eliminating pre-contrast images. Repeated scanning of identical areas needs to be minimized and non-enhanced scans need to be avoided unless specifically justified. Where practical, the protocols may allow all, or as much as possible, of the information required to be obtained during one scan.

A lower dose needs to be used for non-enhanced or repeat scans unless high quality is needed. Follow-up CT scans are not to be performed too prematurely

when, according to the known biology of the disease, one cannot yet expect a response to treatment. Of the children that have undergone CT scans, approximately one third have had at least three scans [122]. Justification for repeat scans needs to be as rigorous as for the first examination, and alternative investigations may suffice.

There is also evidence suggesting how dependent usage is on the physician's environment. This is often felt to be driven by concerns about litigation, heavy workload and pressure to make a rapid diagnosis. As mentioned in earlier sections, clinical audit of justification can be an effective tool in providing an incentive to reduce overutilization. The case for development and use of guidelines and for clinical audit of justification has recently been reviewed [17, 21].

As mentioned earlier, a programme of informing parents about the radiation risks associated with relatively high dose procedures and the benefits of the procedure is advisable. With the higher doses involved in many CT examinations, providing adequate information to the patient, parents and carers and comforters takes on much greater importance. In addition, the question of an appropriate level of information is not trivial. It is worth noting that there have been studies in which parents are given information regarding the risks and benefits of CT. This did not result in reduced acceptance but it did result in more informed questions being put to the care providers [10, 23, 24]. In the long run, while time consuming, this is beneficial.

6.2. OPTIMIZATION IN COMPUTED TOMOGRAPHY

Many aspects of the acquisition of a study affect radiation dose and image quality. These are required to be optimized. Some of the measures necessary to achieve this are relatively simple, as indicated in the recommendations summarized from various sources in Table 25 [7, 9, 10].

Optimization is facilitated if the patient is well prepared, so that the examination can proceed smoothly. Renal function needs to be checked and confirmed, and hydration verified where relevant. Intravenous lines need to be placed well in advance. Whatever steps are desirable to reduce anxiety and to restrict movement need to be taken, including avoiding pain and, where valuable, the use of medication, sedation, anaesthetics, and immobilization and positioning aids, etc. Appropriate information needs to be provided to both the patient and accompanying persons.

These steps reduce or eliminate movement of the patient and the associated degradation of image quality. Image noise, contrast and artefacts have an important influence on study quality. Factors such as scan time and pitch, which

TABLE 25. GENERIC AND SPECIFIC REQUIREMENTS FOR OPTIMIZATION IN COMPUTED TOMOGRAPHY

Generic requirements
The patient and accompanying person(s) need to be informed and prepared.
It is necessary to be familiar with CT dose descriptors.
It needs to be realized that noise reduction means high doses; noise is acceptable if the scan is diagnostic.
It needs to be ensured that operating conditions balance image quality and radiation exposure.
Scan parameters within the axial plane need to be considered in optimization.
A set of tube current settings for paediatric examinations needs to be considered in optimization.
Scan parameters for volume coverage need to be optimized.
A minimal length needs to be scanned, and repeated scanning of identical areas needs to be minimized.
Specific measures that assist these objectives
mAs/baseline mA needs to be reduced according to body weight and/or diameter or composition.
x–y-plane dose modulation needs to be used.
Tube filtration needs to be increased (if available).
A maximal slice thickness appropriate for specific diagnosis needs to be used.
The X ray tube voltage (kVp) needs to be decreased for thin patients.
Normally, the shortest rotation time available needs to be used.
A representative volume sample needs to be used when the entire volume is not needed.
A spiral scan with a pitch greater than 1 (e.g. 1.5) needs to be used, provided this does not automatically increase the mA.
Thicker collimation with overlapping reconstruction needs to be used when thin slices are not needed.
z axis dose modulation needs to be used.
It is necessary to be restrictive in defining uppermost and lowermost limits.
A localizing projection scan extending just minimally beyond scan limits needs to be used.
Additional thick noise-reduced slices need to be reconstructed without an increase in exposure.
Major overlap needs to be avoided when scanning adjacent areas with different protocols.
Non-enhanced scans need to be avoided unless specifically justified.
The protocol needs to be optimized to obtain all of the information requested during one scan.
The number of scans in multiphase scanning needs to be minimized.
In the case of multiphase scanning, a shorter scan length needs to be used for additional scans.
A lower dose needs to be used for non-enhanced or repeat scans unless high quality is needed.
A minimal number of additional sequential functional scans needs to be used.
Length of scans and fluoroscopy time need to be minimized in interventional applications.
Test bolus and/or bolus triggering needs to be replaced by standard scan delay unless timing is very critical.
Additional protection devices need to be used where indicated (lens, thyroid, breast, gonads).

can be chosen, may affect the presence or absence of artefacts from motion. With faster table speed and gantry rotation, breathing artefacts in children may be reduced.

In addition to the absolute quality of the image, it is necessary to be attentive to both the requirements of the diagnostic problem being posed and the natural contrast levels available in the area being imaged. For example, the image quality and dose necessary to visualize large bony structures may be less than those required to demonstrate fine vascular structure. Alternatively, more image noise may be acceptable in skeletal or lung parenchymal examinations than in brain or abdominal examinations, owing to the higher contrast differences in the former. Thus, a chest examination with higher noise may have the same diagnostic quality as a lower noise abdominal study.

Abdominal organs, such as the liver, kidney and pancreas, may show only minimal density differences between normal tissues and pathological lesions, and will consequently require higher doses to provide the signal to noise ratio required for acceptable differentiation. Thus, acceptable scan quality will be influenced by the clinical indication for the study. 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 metastases.

The perception of study quality is also related to the display of the data. Three dimensional reconstruction to determine bony outlines for surgical planning may be achieved at relatively low doses [9]. As with all digital studies, the quality and adjustment of the display can have a significant impact on the quality of the final image displayed. A study viewed on the CT console may look inferior when viewed on a monitor which is not set up for viewing examinations. The ambient environment for image review will also be reflected in the perceived study quality [102].

In reducing dose while maintaining diagnostic image quality, the presence of noise needs to be accepted as long as diagnostic quality is not lost. Some suppliers now provide advice on noise levels and suggest values which can be suitable for initial examinations, and different values which may be appropriate for follow-up or repeat procedures. Extra technical information on how to approach these possibilities is provided in Appendix V.

From a different perspective, breast tissue has to be protected in children, without interfering with image quality. Bismuth breast shields are now available for all paediatric age groups, from neonate to young adult. When used in an appropriate setting, the bismuth shielding technique is still a valid and valuable tool for reducing radiation risk in children [126]. Bismuth breast shields need to be routinely used for examinations involving breast tissue. When z axis modulation is used, it is desirable for them to be positioned after the localizer has

been performed [127]. However, caution is raised based on recent results which need to be kept in view to rationalize use of shielding [128].

The recommendations in Tables 24 and 25 are summarized from a number of sources [7, 10, 123]. While many are technically simple and could well be applied to radiology in general, they are repeated here because their importance in CT has sometimes been missed, and because they are important for those planning a practical approach to dose reduction. Giving effect to them as a matter of institutional policy requires a broad commitment and team approach on behalf of the many professionals and individuals involved.

The Image Gently Campaign emphasizes and draws attention to this; its recommendations for successful widespread application are summarized in Table 26 [10]. In the long term, additional initiatives are required and some of these are summarized in Table 27. Table 27 was developed from an NCI original but has a number of additional recommendations [7].

6.3. COMPUTED TOMOGRAPHY AND DIAGNOSTIC REFERENCE LEVELS

The area of CT dose measurement is unsatisfactory, in that it lacks transparency for many end users. Among the reasons for this are the many different metrics used for CT dose. At least three are commonly employed by the medical physics community. These are CT dose index over the entire volume scanned ($CTDI_{vol}$), dose length product (DLP given in mGy · cm) and absorbed

TABLE 26. ADVICE FOR RADIOLOGISTS, MEDICAL PHYSICISTS AND TECHNOLOGISTS FROM THE IMAGE GENTLY CAMPAIGN [10]

Awareness of the need to decrease CT radiation dose to children needs to be improved.
It is necessary to be committed to making a change in daily practice through teamwork between radiologists, medical radiation technologists, referring doctors and parents.
Medical physicists, radiologists and medical radiation technologists need to review CT protocols and ‘down-size’ them for children.
Single phase scans are often adequate. Pre- and post-contrast or delayed scans rarely add additional information in children but can double or triple the dose.
Only the indicated area needs to be scanned. If a patient has a possible dermoid on ultrasound, there is rarely a need to scan the entire abdomen and pelvis.
It is necessary to be involved with the patients and to be their advocate. It is necessary to ask the questions required to ensure that the scan is ‘child-sized’, and only the area required needs to be scanned.

TABLE 27. LONG TERM STRATEGIES TO MINIMIZE PAEDIATRIC COMPUTED TOMOGRAPHY RADIATION *(based on National Cancer Institute recommendations [7])*

Further development of referral and/or appropriateness criteria needs to be encouraged.
Further development and adoption of paediatric CT protocols need to be encouraged.
Clinical audit for justification needs to be encouraged.
The use of selective strategies for paediatric imaging, such as for the pre-surgical evaluation of appendicitis, needs to be encouraged.
Industry and technical standards organizations need to be encouraged to produce innovative standardized designs that address the issues of dose management for children.
Further research needs to be conducted to determine the relationship between CT quality and dose, to customize CT scanning for individual children, and to clarify the relationship between CT radiation and cancer risk.
Journal publications and conferences need to be used to educate within and outside radiology specialties to manage exposure settings for optimization purposes and to assess the individual need for CT.
Information needs to be disseminated through associations, organizations or societies involved in health care of children.
Readily available information sources on the Image Gently Campaign, IAEA Radiation Protection of Patients and other relevant web sites need to be provided [10, 20].

dose (mGy). Other metrics are also often used. In addition, effective dose (given in millisieverts) is frequently quoted, as it conveniently relates to risk, but there are some reservations about this in the measurement community.

Discussion of these quantities and measurement systems is beyond the scope of this volume but they are reviewed at length and summarized in many sources [129–133].

Some typical paediatric CT effective doses in millisieverts and organ doses in milligrays from the US NCI are reproduced in Table 28. The latter refers to the absorbed doses in particular organs (mGy) and the former to effective dose, which is a marker for whole body risk. Reference doses and typical doses from various sources are available in a series of publications [7, 10, 134–139].

The NCI makes the following observations:

> "Effective doses from a single paediatric CT scan can range from about <1 to 30 mSv. Among children who have undergone CT scans, approximately one-third have had at least three scans. Multiple scans present a particular concern. In addition, more than one scan 'phase' may be done during a single examination, further increasing the radiation dose. A single scan

TABLE 28. TYPICAL COMPUTED TOMOGRAPHY DOSES [7]

Examination type	Relevant organ	Range of absorbed organ dose (mGy)	Range of effective dose (mSv)
Head unadjusted (200 mAs)	Brain	23–49	1.8–3.8
Head adjusted (100 mAs)	Brain	11–25	0.9–1.9
Abdomen unadjusted (200 mAs)	Stomach	21–43	11–24
Abdomen adjusted (50 mAs)	Stomach	5–11	6–12
Chest X ray PA	Lung	0.04–0.08	0.01–0.03
Chest X ray lateral	Lung	0.04–0.10	0.03–0.06

Note: 'Unadjusted' refers to using the same settings as for adults; 'adjusted' refers to settings adjusted for body weight; PA: postero-anterior.

during paediatric CT may be sufficient in the vast majority of cases. The highest lifetime risks estimated in the literature are less than 1 in 1000, and most estimates are substantially lower than that. The public health issue is the increasingly large paediatric population being exposed to these small risks. The benefits of properly performed CT examinations must always outweigh the risks for an individual child" [7].

In practice, in potentially life threatening situations, multislice CT can be an excellent tool. Good protocols are needed to ensure that the study is both justified and optimized [139].

Table 29 provides information on CT doses in terms of the equivalent period of natural background. There are also representations in terms of equivalent number of chest X rays for each examination [20]. It can be seen that this has considerable value in communicating with both patients and physicians. Some radiologists have questioned the use of these scales on the grounds that patients or guardians may find it frightening to have a scan that is equivalent to several hundred chest X rays or many years of natural background radiation. However, in the interests of patients, it is essential that a readily comprehensible measure of dose and risk be available, as well as a sense of the real benefit to be derived from the scan.

In Table 30, examples of United Kingdom national reference doses for paediatric patients from various age groups and for different examinations are provided [138], which are a valuable benchmark for practitioners. The weighted CT dose index ($CTDI_w$) values are provided for the purpose of comparison with historical values as this index has largely been replaced by $CTDI_{vol}$ as a reference dose quantity. The reader is referred to the original publication for the full detail of the conditions that prevailed for the various measurements reported [138].

TABLE 29. TYPICAL DOSES FROM VARIOUS EXAMINATIONS, EXPRESSED AS EFFECTIVE DOSE AND IN EQUIVALENT PERIOD OF NATURAL BACKGROUND WITH ASSOCIATED INCREASED CANCER RISK [20]

Procedure	Effective dose (mSv)	Increased risk of cancer	Equivalent period of natural background
No dose (MRI, ultrasound)	Not defined and/or applicable	Not known	Not equivalent
Low dose (chest X ray, extremities)	<0.1	1 in 1 million	Few days
Intermediate dose (intravenous pyelogram, lumbar spine, abdomen, head and neck CT)	1–5	1 in 10 000	Few months to a few years
Higher doses (chest or abdomen CT, nuclear cardiogram, cardiac angiogram, barium enema)	5–20	1 in 2000	Few years to several years
Natural background	2.4	1 in 5000	—

Shrimpton et al. compare some of these reference levels with those that previously prevailed in Europe. In commenting on their findings, they have many useful observations to make and conclude in respect of paediatric practice that:

> "For examinations on children, typical values of the dose descriptors…, $CTDI_{vol}$ and DLP decrease with decreasing age (and size), whereas the corresponding effective dose increases. Indeed, effective doses to children aged 0–1 years from examinations of the head and the chest were typically higher than those for adults" [138].

Other recent national surveys of paediatric CT doses are available, together with some experience of the potentially positive impact of introducing reference levels [134, 136, 139]. Table 31 reproduces the recommendations of Verdun et al. for DRLs in Switzerland. They also usefully compare their findings with recent work and/or recommendations from the United Kingdom and Germany [138, 140]. It is not clear that, in all cases, like is being compared with like, but nonetheless the comparisons are reassuring and useful. Additional information on conversion of DLP to effective dose is provided in Appendix V.

A recent large scale multinational study by the IAEA investigated the frequency of CT examinations of paediatric patients below 15 years of age in 28 countries of Africa, Asia and Eastern Europe, and assessed the magnitude of

TABLE 30. NATIONAL REFERENCE DOSES FOR COMPUTED TOMOGRAPHY OF PAEDIATRIC PATIENTS IN THE UNITED KINGDOM *(published in 2006 following a 2003 review, compared with European Commission values from 1999 [138, 139])*

Examination	Region	$CTDI_w$ (mGy)[a]		$CTDI_{vol}$ (mGy)[a]	Dose length product (mGy · cm)[a]	
		United Kingdom 2003 [138]	Europe [139]	United Kingdom 2003 [138]	United Kingdom 2003 [138]	Europe [139]
Chest (detection of malignancy)	Whole examination					
0–1 year old		23	20	12	200	200
5 year old		20	30	13	230	400
10 year old		26	30	20	370	600
Head trauma (including non-accidental injury)	Post-fossa	35	—	35	—	—
	Cerebrum	30	—	30	—	—
0–1 year old	Whole examination	—	40	—	270	300
Head trauma (including non-accidental injury)	Post-fossa	50	—	50	—	—
	Cerebrum	45	—	45	—	—
5 year old	Whole examination	—	60	—	470	600
Head trauma (including non-accidental injury)	Post-fossa	65	—	65	—	—
	Cerebrum	50	—	50	—	—
10 year old	Whole examination	—	70	—	620	750

Note: $CTDI_w$: weighted CT dose index; $CTDI_{vol}$: CT dose index divided by volume scanned.
[a] Relates to the 16 cm diameter CT dosimetry phantom.

CT doses. Radiation dose data were available from 101 CT facilities in 19 countries [141].

The results show that, on average, the frequency of paediatric CT examinations was 20, 16 and 5% of all CT examinations in participating centres in Africa, Asia and Eastern Europe, respectively. The mean frequencies of paediatric CT examinations ranged from 0.5 to 38% among different countries. The survey data indicated a relatively higher paediatric CT frequency in a majority of African countries than in Asia and Eastern Europe. In the countries included in this study, the paediatric CT frequency in Asian countries is also relatively higher than in Eastern Europe. This situation is likely to be due to the

TABLE 31. DIAGNOSTIC REFERENCE LEVELS (mGy FOR COMPUTED TOMOGRAPHY DOSE INDEX AND mGy · cm FOR DOSE LENGTH PRODUCT) FOR DIFFERENT PATIENT GROUPS AND EXAMINATIONS IN SWITZERLAND, GERMANY, THE UNITED KINGDOM AND THE EUROPEAN UNION *(adapted from Verdun [134])*

Age group (a)[a]	Quantity	Examination			
		Brain			
		Switzerland [134]	Germany	United Kingdom	European Union
<1	$CTDI_{vol}$	20	33	30	—
	DLP	270	390	270	300
1–5	$CTDI_{vol}$	30	40	45	—
	DLP	420	520	470	600
5–10	$CTDI_{vol}$	40	50	50	—
	DLP	560	710	620	750
10–15	$CTDI_{vol}$	60	60	65	—
	DLP	1000	920	930	—
		Chest			
		Switzerland [134]	Germany	United Kingdom	European Union
<1	$CTDI_{vol}$	5	3.5	12	—
	DLP	110	55	200	200
1–5	$CTDI_{vol}$	8	5.5	13	—
	DLP	200	110	230	400
5–10	$CTDI_{vol}$	10	8.5	20	—
	DLP	220	210	370	600
10–15	$CTDI_{vol}$	12	6.8	14	—
	DLP	460	205	580	—
		Abdomen			
		Switzerland [134]	Germany	United Kingdom	European Union
<1	$CTDI_{vol}$	7	5	20[a]	—
	DLP	130	145	170[a]	—
1–5	$CTDI_{vol}$	9	8	20[a]	—
	DLP	300	255	250[a]	—
5–10	$CTDI_{vol}$	13	13	30[a]	—
	DLP	380	475	500[a]	—
10–15	$CTDI_{vol}$	16	10	14	—
	DLP	500	500	560	—

Note: $CTDI_{vol}$: CT dose index divided by volume scanned; DLP: dose length product.

[a] For the United Kingdom, adult values were taken for the age group 10–15 years, as values for this age group were not available in the report.

non-availability of alternative imaging modalities, such as MRI or high resolution ultrasound, and/or possibly limited experience in justifying CT procedures for children.

The $CTDI_w$ variations ranged up to a factor of 55 (Africa), 16.3 (Asia) and 6.6 (Eastern Europe). The corresponding DLP variations ranged by a factor of 10, 20 and 8, respectively. Eleven CT facilities in six countries were found to use adult CT exposure parameters for paediatric patients. This single factor has great implications for the individual dose, collective dose and risk of lifetime radiation induced cancer. Variations in $CTDI_w$ and DLP across countries are not unexpected as similar variations have been presented in earlier studies from a number of developed countries and are attributable to different techniques used for CT examinations.

The typical mean $CTDI_w$ and DLP values with associated ranges in three regions are presented in Table 32. In this study, CT equipment dose characteristics are reported in terms of $CTDI_w$ because the majority of centres reported this quantity in view of older CT scanners. For those reporting in $CTDI_{vol}$, the values of $CTDI_w$ were computed using pitch factors.

TABLE 32. MEAN WEIGHTED COMPUTED TOMOGRAPHY DOSE INDEX AND DOSE LENGTH PRODUCT VALUES WITH ASSOCIATED RANGES FOR SELECTED PAEDIATRIC COMPUTED TOMOGRAPHY EXAMINATIONS IN THREE REGIONS [141]

Region	Weighted CT dose index (mGy)				
	Chest	Chest — high resolution	Lumbar spine	Abdomen	Pelvis
Africa	10 (4–17.1)	9.8 (3.5–14)	14 (4.2–14)	8.5 (4.2–20)	8.3 (4.9–17)
Asia	10 (5.5–16)	13 (5.2–19)	13 (8.7–18)	14 (8.7–20)	14 (8.7–18)
Europe	8.7 (3.3–16)	6.5	11 (7.1–22)	9.2 (3.5–14)	9.3 (3.9–14)
	Dose length product (mGy · cm)				
Africa	153 (85–272)	137 (49–371)	201 (121–277)	180 (43–320)	131 (50–382)
Asia	269 (134–216)	139 (64–260)	274 (150–397)	413 (150–821)	189 (150–240)
Europe	194 (76–326)	145 (96–194)	182 (115–385)	246 (115–613)	255 (82–487)

The study indicated a stronger need in many developing countries to justify CT examinations in children and for their optimization. As an example, implementation of suitable dose reduction methods and follow-up of the facilities that use CT exposure parameters for children's CT examinations were applied in Sudan and Thailand in consultation with radiologists. Consequently, based on the reported new scan parameters, a $CTDI_w$ reduction in the range of 38–50% was reported for chest CT in Sudan, and 53% for the same type of CT procedure in Thailand.

This study has established baseline data on the frequency and dose levels in paediatric CT examinations. This will form a basis for future studies on dose management in paediatric CT examinations. In that sense, the ongoing large scale paediatric CT dose survey organized by the IAEA is an important step in the optimization of paediatric CT practice and for promotion and implementation of dose reduction strategies, while maintaining diagnostic information worldwide. Furthermore, education and training programmes currently being implemented by the IAEA in developing countries, along with focused training on radiation dose management organized by the IAEA for participants in the project, provide key resources directed at increased awareness of radiation dose management methods in CT.

6.4. SPECIAL TECHNIQUES IN COMPUTED TOMOGRAPHY

6.4.1. Computed tomography interventions

Once a diagnostic scan has been performed, the CT dose used for the interventional procedure can be reduced markedly. Repeated imaging has to be limited to the small area of interest directly involved in the procedure. Where possible, a single slice may be used.

6.4.2. Cone beam dental computed tomography

CT based systems are finding significant application in dental practice, and intensive study of the requirements for justification is necessary. These and other developments are the subject of the SEDENTEXCT EC project [142]. The principles for use of dental cone beam CT have been set out by the European Academy of Dental and Maxillofacial Radiology in a consensus document from which an extract is provided in Table 33 [142]. Much of this guidance deals with justification issues but training and optimization issues are also emphasized.

TABLE 33. USE OF DENTAL CONE BEAM COMPUTED TOMOGRAPHY [142]

Cone beam CT examinations need not be carried out unless a history and clinical examination have been performed.

Cone beam CT examinations are required to be justified for each patient to demonstrate that the benefits outweigh the risks.

Cone beam CT examinations need to potentially add new information to aid the patient's management.

Cone beam CT ought not to be repeated 'routinely' on a patient without a new risk–benefit assessment having been performed.

When accepting referrals from other dentists for cone beam CT examinations, the referring dentist needs to supply sufficient clinical information (results of a history and examination) to allow the cone beam CT practitioner to perform the justification process.

Cone beam CT need only be used when the question for which imaging is required cannot be answered adequately by lower dose conventional (traditional) radiography.

Cone beam CT images need to undergo a thorough clinical evaluation ('radiological report') of the entire image data set.

Where it is likely that the evaluation of soft tissues will be required as part of the patient's radiological assessment, the appropriate imaging needs to be conventional medical CT or MRI, rather than cone beam CT.

Cone beam CT equipment needs to offer a choice of volume sizes, and examinations need to use the smallest volume that is compatible with the clinical situation if this provides less radiation dose to the patient.

Where cone beam CT equipment offers a choice of resolution, the resolution compatible with adequate diagnosis and the lowest achievable dose needs to be used.

A quality assurance programme needs to be established and implemented for each cone beam CT facility, including equipment, techniques and quality control procedures.

Aids to accurate positioning (light beam markers) always need to be used.

For dento-alveolar cone beam CT images of the teeth, their supporting structures, and the mandible and the maxilla up to the floor of the nose (e.g. 8 cm $\times$ 8 cm or smaller fields of view), a clinical evaluation ('radiological report') needs to be undertaken by a specially trained dental and maxillofacial radiologist or, where this is impracticable, an adequately trained general dental practitioner.

For non-dento-alveolar small fields of view (e.g. temporal bone) and all craniofacial cone beam CT images (fields of view extending beyond the teeth, their supporting structures, the mandible, including the temporomandibular joint, and the maxilla up to the floor of the nose), a clinical evaluation ('radiological report') needs to be undertaken by a specially trained dental and maxillofacial radiologist or by a clinical radiologist (medical radiologist).

7. NUCLEAR MEDICINE

Nuclear medicine investigations are an important component of the overall imaging armamentarium used in paediatric imaging. The general provisions for patient and staff safety in nuclear medicine are not addressed in this section as these are beyond the scope of this publication, and are widely available from many sources [4, 143, 144]. This section is limited to aspects of safety in nuclear medicine that have specific paediatric applications. Some additional practical information is provided in Appendix VI.

7.1. JUSTIFICATION IN NUCLEAR MEDICINE

As with other imaging modalities, nuclear medicine studies are required to be rigorously justified. Large individual and population doses arising from nuclear medicine activity in some countries are, at least in part, attributable to some overutilization and to questionable referral patterns. Alternative modalities, such as ultrasonography (e.g. in the assessment and follow-up of renal abnormalities) and MRI, have to be considered (e.g. in assessing bone lesions which involve the bone marrow and surrounding soft tissues). However, nuclear medicine studies, including renography and bone scans, continue to be useful and are regularly performed in children.

Some advice on nuclear medicine referrals is available in Ref. [28]. The advice of earlier sections needs to be followed in relation to information provided to the patient, development of local protocols for referral, clinical audit of justification, and communication with the patient, their carers and comforters, their parents and the referring physician.

7.2. OPTIMIZATION AND DOSE REDUCTION IN NUCLEAR MEDICINE

The radiopharmaceutical activity given to paediatric patients has to be the minimum amount necessary to ensure a satisfactory examination. High activity (which does not result in improved diagnostic accuracy or sensitivity) or low activity (which does not permit an adequate scan) are both unacceptable, as they are both likely to give rise to unnecessary radiation exposure.

A work group composed of paediatric nuclear medicine physicians, medical radiation technologists and medical physicists, representing the Society of Nuclear Medicine, the Society for Paediatric Radiology and the American College of Radiology, recently issued consensus guidelines for administered

radiopharmaceutical activities in children and adolescents [10]. The guidelines were based on a survey conducted at 13 paediatric hospitals in North America indicating that administered radiopharmaceutical activities in children varied widely. The purpose of the work was to fulfil the above mentioned goals of diagnostic nuclear medicine procedures.

In practice, paediatric activity is estimated based on commonly used adult activities, corrected for body weight or body surface area. These activities are generally a good guide for children over 1 year of age [145–148]. Effective dose for a paediatric patient will depend upon the method used for adjustment of radionuclide activity (body surface area or body weight). If the body weight approach is used, the effective dose for children will be comparable to that for an adult [1]. Effective doses from diagnostic nuclear medicine procedures are given in Table 34.

The DRL in nuclear medicine is specified as the activity administered to the child. Table 35 illustrates a set of DRLs used in Ireland for seven radiopharmaceuticals for children of various ages, and for adults. These are consistent with practice elsewhere in Europe. These activities can be compared with the often higher median activity per kilogram used in the USA (Table 36), based on a survey of a number of hospitals in the USA. No DRLs focused on the nuclear medicine component of positron emission tomography (PET) examinations have yet been developed. In the case of PET/CT, the guidelines for CT also have to be followed [149].

Care needs to be taken with the scanning protocol in optimization for paediatric studies. Where appropriate, use needs to be made of electronic magnification, converging collimators for small organs, high sensitivity collimators when there is an advantage in using them, and appropriate choice of radiopharmaceuticals (e.g. MAG3 instead of DTPA for dynamic renal scans).

From a practical standpoint, there are important considerations particular to infants and small children. The infant or child needs to be well hydrated, and frequent diaper changes are necessary for babies and/or toddlers. Those dealing with infants, and carers and comforters of infants need to have a good knowledge of the radionuclide involved, its half-life, the biodistribution of the radiopharmaceutical form used in the infant and any other pertinent physiological factors.

Positioning of the patient is important during nuclear medicine imaging. Immobilization devices, such as sandbags, pillows, etc., are commonly used. Viewing television or a video during the examination often helps to distract children. In some cases, sedation is required. This may be the case when lengthy procedures, such as single photon emission CT (SPECT), are performed. The type and level of sedation as well as the activity used need to be determined in consultation with the referring clinician.

TABLE 34. EFFECTIVE DOSES FROM TYPICAL NUCLEAR MEDICINE PROCEDURES FOR PAEDIATRIC PATIENTS [1]

Procedure utilizing:	Effective dose (mSv/MBq)			
	15 year old	10 year old	5 year old	1 year old
F-18 FDG	0.025	0.036	0.050	0.095
Ga-67 citrate	0.130	0.200	0.330	0.640
I-123 sodium iodide (0% uptake)	0.016	0.024	0.037	0.037
I-123 sodium iodide (5% uptake)	0.053	0.080	0.150	0.290
I-123 sodium iodide (15% uptake)	0.110	0.170	0.350	0.650
I-123 sodium iodide (25% uptake)	0.170	0.260	0.540	1.000
I-123 sodium iodide (35% uptake)	0.230	0.350	0.740	1.400
I-123 sodium iodide (45% uptake)	0.290	0.440	0.940	1.800
I-123 sodium iodide (55% uptake)	0.350	0.530	1.100	2.100
In-111 pentatreotide	0.071	0.100	0.160	0.280
In-111 white blood cells	0.836	1.240	1.910	3.380
Tc-99m HIDA	0.021	0.029	0.045	0.100
Tc-99m DMSA	0.011	0.015	0.021	0.037
Tc-99m HMPAO	0.011	0.017	0.027	0.049
Tc-99m MAA	0.016	0.023	0.034	0.063
Tc-99m MDP	0.007	0.011	0.014	0.027
Tc-99m MAG3	0.009	0.012	0.012	0.022
Tc-99m ECD	0.014	0.021	0.032	0.060
Tc-99m DTPA	0.006	0.008	0.009	0.016
Tc-99m pyrophosphate	0.007	0.011	0.014	0.027
Tc-99m red blood cells	0.009	0.014	0.021	0.039
Tc-99m sestamibi (rest)	0.012	0.018	0.028	0.053
Tc-99m sestamibi (stress)	0.010	0.016	0.023	0.045
Tc-99m sodium pertechnetate	0.017	0.026	0.042	0.079
Tc-99m sulphur colloid	0.012	0.018	0.028	0.050
Tc-99m tetrofosmin (rest)	0.010	0.013	0.022	0.043
Tc-99m tetrofosmin (stress)	0.008	0.012	0.018	0.035
Tc-99m thallous chloride	0.293	1.160	1.500	2.280

Note: DMSA: dimercaptosuccinic acid; DTPA: diethylenetriaminepentaacetic acid; ECD: ethyl cysteinate dimer; FDG: fluorodeoxyglucose; HIDA: hepatobiliary iminodiacetic acid; HMPAO: hexamethylpropyleneamine oxime; MAA: macroaggregate of albumin; MAG3: mercaptoacetyltriglycine; MDP: methylene diphosphonate.

TABLE 35. PAEDIATRIC DIAGNOSTIC REFERENCE LEVELS (MBq) FOR COMMONLY PERFORMED DIAGNOSTIC PROCEDURES [145]

Radiopharmaceutical	Paediatric diagnostic reference level (MBq)					
	Newborn (5 kg)	1 year old (10.5 kg)	5 year old (19.5 kg)	10 year old (33 kg)	15 year old (64.5 kg)	Adult (70 kg)
Tc-99m phosphonates (bone)	43	90	167	283	549	600
Tc-99m DMSA	15	15	28	47	91	100
Tc-99m DTPA	20	33	61	104	201	220
Tc-99m MAG3	15	15	28	47	91	100
Tc-99m pertechnetate thyroid	10	12	22	38	73	80
Tc-99m pertechnetate Meckel's	28	58	107	182	352	385

Note: DMSA: dimercaptosuccinic acid; DTPA: diethylenetriaminepentaacetic acid; MAG3: mercaptoacetyltriglycine.

Stabin et al. present effective and absorbed dose estimates for children of different ages, for different nuclear medicine procedures, using standard medical internal radiation dose methodology [150]. Effective doses per unit of administered radiopharmaceutical (mSv/MBq) have also been calculated using five paediatric phantoms for a number of radiopharmaceuticals commonly used in children.

Values of effective dose resulting from the application of the weight/surface area schedules of administered radiopharmaceutical proposed by the paediatric task group of the European Association of Nuclear Medicine are also available. Although some values of effective dose exceed 10 mSv for the surface area schedule, the majority are less than 5 mSv [151].

As mentioned in Section 2.5, arrangements to deal with the unintended administration of activity to patients are required. This may be more sensitive in paediatric nuclear medicine than in radiology, even when the dose is lower. Good, well conceived and well tested systems to provide fail-safe protection against misadministration need to be part of the operational policy of every department.

When a paediatric patient receives the incorrect amount of radiopharmaceutical or when the incorrect radiopharmaceutical is administered, this needs to be reported within the hospital and investigated, as discussed in Section 2.5, with a view to implementing corrective actions to reduce the likelihood of recurrence of such an incident. The patient and/or the parent and/or guardian and/or carers and comforters have to be informed. In some countries, it is also mandatory to report incidents of this type to the regulatory authorities or medical authorities (Section 2.5).

TABLE 36. MEDIAN ACTIVITY PER KILOGRAM OF BODY WEIGHT INJECTED INTO PAEDIATRIC PATIENTS (*adapted from Ref. [146]*)

Radionuclide and marker	Median activity (MBq/kg)
Tc-99m DMSA	2.22
Tc-99m MAG3	5.55
Tc-99m MDP	11.10
Tc-99m DISIDA	2.78
I-123 MIBG	5.55
Tc-99m $NaTcO_4$ for Meckel's	5.18
I-123 NaI for thyroid	0.10
Tc-99m ECD or HMPAO	10.55
Tc-99m MIBI	12.95
Tc-99m MAA	1.85
Tc-99m ultratag for gastrointestinal	8.33
Tc-99m ultratag for multiple gated acquisition	8.14
Tc-99m denatured red blood cells	2.22
Ga-67 inflammatory disease	1.85
Ga-67 tumour imaging	4.07
F-18 FDG	5.37

Note: DISIDA: di-isopropyliminodiacetic acid; DMSA: dimercaptosuccinic acid; ECD: ethyl cysteinate dimer; FDG: fluorodeoxyglucose; HMPAO: hexamethylpropyleneamine oxime; MAA: macroaggregate of albumin; MAG3: mercaptoacetyltriglycine; MDP: methylene diphosphonate; MIBG: metaiodobenzylguanidine; MIBI: methoxyisobutylisonitrile.

8. SUMMARY AND CONCLUSIONS

The context for this report is the increasing use of paediatric radiology, increasing doses from individual examinations and increasing concern about the resulting potential harm that may arise to children. It is, therefore, important to emphasize that most paediatric radiology is necessary and of great benefit to the children examined.

Sections 1–7 establish the need to attend to the features of radiology of younger persons that distinguish it from adult radiology. In addition, they provide a considered range of tools to deal with the problems arising from these differences. The special requirements that arise apply to all aspects of the radiation protection system, including justification with its associated processes, and the multifaceted task of optimization, including the use of DRLs and dose constraints. All of these help guide those involved in service delivery towards good practice. The radiological techniques to which these approaches are applied include all radiology, including general screen film and DR, dental and mobile radiography, fluoroscopy, interventional procedures and CT.

The requirement for justification has been emphasized as some workers estimate that a significant fraction of paediatric examinations are not justified. Until recently, it was felt that there was little that might be done to assess and facilitate justification in practice. However, throughout this publication, a number of tools are proposed and offered to facilitate justification. These include:

— Use of evidence based referral guidelines and local protocols, where available;
— Use of clinical audit of justification (including appropriateness of examinations).

These will ensure that the justification protocols and/or processes are well formulated. Examinations will only be conducted when appropriate and necessary, and due regard will be paid to an appropriate process for providing information to the patient and family. When available, alternative techniques such as ultrasound and MRI will be used. Close attention will be paid to previous procedures and the information available from the referring practitioner, the patient and their family.

With respect to optimization, many initiatives are necessary and are detailed in the preceding sections on particular techniques. The following core points apply generically to almost all of the techniques:

— All persons directing and conducting medical exposure of children, including radiologists and technologists, have to have received recognized education and training in their discipline, including in radiation protection, and specialist training in its paediatric aspects.
— Care needs to be taken with procurement of equipment to ensure that it is specified, supplied and acceptance tested in accordance with international technical standards. A team approach to each stage needs to be taken, and may involve a medical physicist. The specification needs to explicitly include the relevant paediatric features.
— All examinations need to be conducted using 'child-sized' protocols and/or exposures, which have been developed using a team approach involving radiological medical practitioners, medical radiation technologists, medical physicists, supplier application specialists and engineers.
— Additional training specific to each item of equipment, using the team approach, is essential to ensure that all staff will adopt and continue to use the 'child-sized' protocols. Protocols for repeat and/or confirmation procedures need to be reduced to the views essential for the management of the patient.
— Practice in a department may be audited periodically with respect to an index for patient dose. This needs to be compared with local, regional or national DRLs. It is necessary to be aware of the DRLs appropriate to the region.
— An ongoing quality assurance programme, using a team approach, needs to be employed and may be managed as part of a clinical audit programme.
— Dose indication is essential on interventional, CT and fluoroscopy equipment, and is desirable on other equipment.
— There is a serious lack of good up to date data on reference doses in all areas of paediatric radiology, including high dose areas such as CT and interventional radiology. The lack also extends to lower dose areas such as radiography and dental examinations.
— It is necessary to become aware of the possibility of unnecessarily or inadvertently using high doses, particularly with CT, interventional radiology and all digital systems. It is necessary to become informed on how to prevent this.
— Carers and comforters, and those who help restrain children during procedures are not to be members of hospital or clinic staff. They may, for example, be members of the patient's family, and may knowingly and willingly offer their service within a medical framework to which an age related dose constraint is applied.
— Collimation needs to be tight, and additional shielding of sensitive areas (e.g. breast, gonads, thyroid, eyes) has to be employed where practicable.

— When ‘child-sized’ protocols have not been explicitly supplied, developed and/or verified as appropriate, manual exposures need to be used.
— The image receptor normally has to be as close to the patient as possible and the X ray tube has to be as far away as is practical for the protocol being followed.
— As a general rule, anti-scatter grids need not be used with small children.
— Where practicable, all X ray examinations need to be performed on fixed units in the relevant department. The use of mobile X ray units needs to be limited to those patients who cannot be moved to a fixed X ray unit.
— For female children who are or may be pregnant, special precautions are necessary.
— Staff are not to be in the room when exposures are ongoing unless this is absolutely necessary. Generally, this is only the case during interventions and when conducting fluoroscopy. Staff who have to be in the room in such circumstances require additional special training.

The particular requirements for each modality are detailed in the appropriate section.

Finally, while the above considerations are valuable in initiating the processes of justification and optimization as envisaged in the BSS, they are not comprehensive. Much remains to be done in further resolving the appropriate referral patterns, optimization of technique and developing guidance or reference levels in paediatric radiology in a fast changing technology. The advice presented here will inform the recommendations in the revised Safety Guide [6], as well as assist States in complying with the requirements of the BSS.

Appendix I

BIOLOGICAL EFFECTS OF RADIATION IN CHILDREN

The biological effects of ionizing radiation in children depend on their radiosensitivity, their life expectancy and their radiation exposure. In practice, at the same effective dose, the biological effects and lifetime risks can be expected to be higher in a child than in an adult [11, 13, 14]. However, the extent of the increase is not definitively established and there is a lack of agreement on how best to present it.

Organs and tissues are distributed differently and are more susceptible to radiation during childhood. A CT examination of the lower extremities will, in bone marrow, encounter almost exclusively fatty marrow in an adult. In a child, in the same examination, a significant proportion of the red marrow will be exposed and is, therefore, a much greater cause for concern [9].

It is also suggested that at the cellular and subcellular levels, proliferation during growth periods is likely to be associated with increased susceptibility. As most malignant tumours become manifest many years after exposure, adult patients may have died from other causes before induced cancers are expressed. Children, because of their longer life expectancy, have a higher chance of being alive at the time of tumour presentation.

A framework for dealing with the risk of incidence and fatality from radiation induced cancers is provided by the ICRP and is broadly based on the approach to biological effects of radiation set out in the BEIR Report [11–14]. The combined impact of these reports is to indicate a substantial increase in lifetime risk among those irradiated during childhood. There are also substantial gender differences.

Attempts have been made to summarize the data and produce a single figure defining the relative sensitivities of children as opposed to adults. The values tend to vary from unity up to about four depending on age, and the values cited in the literature for increases in the impact expected in paediatric patients are usually two to three. The net impact of these assessments is a view that there are significant cancer risks associated with some forms of paediatric radiology, particularly when vigorous measures for justification and optimization are not taken [16, 152].

The following considerations may help to illustrate the problem. In infant girls, the risk may be up to ten times that for an adult. The risk is higher for girls than for boys. The overall fatal risk coefficient is approximately 5% per sievert for the whole population. The coefficient may only be 3% for the subset of the population over 50 but can be as high as 15% for younger children [153, 154].

Thyroid, lung, breast tissue and bone marrow are characterized by higher radiation sensitivity during childhood. A breast dose of 10 mGy to a female, received before 35 years of age, will increase the spontaneous breast cancer rate by 14% [153, 155, 156]. Scoliosis patients have a larger number of X rays when they are children or young adults. Table 37, from a study performed on a cohort of almost 5000 scoliosis patients, suggests that at relatively low doses excess breast cancer deaths can occur. It is thought this could possibly be because the exposure took place at a time when the breast appears to be especially sensitive to radiation [157].

Children are also sometimes further at risk because of unnecessary examinations and the increased dose received in examinations [16, 152]. For example, as stated in many places in the text, children still continue to receive higher doses because of inappropriate protocols or unsuitable AEC systems, particularly in CT.

In addition to these unwarranted increases, there are circumstances in which the dose to children may need to be increased. For example, they have thinner layers of abdominal visceral fat and, thus, lack the associated natural contrast usually available in adults. As a result, increased radiosensitivity is compounded by additional radiation, some necessary and some unnecessary.

TABLE 37. BREAST CANCER MORTALITY AND DIAGNOSTIC X RAYS FOR SCOLIOSIS [157]

4822 exposed, 644 not exposed
Mean age at exposure: 10.6 years
Mean dose: 0.11 Gy
70 observed cancers
35.7 expected

Appendix II

EXTRACT FROM THE EUROPEAN COMMISSION'S REFERRAL GUIDELINES FOR IMAGING

A representative version of the referral guidelines for paediatric radiology published by the EC in 2008 is adapted in Table 38 [28, 29]. They are part of a larger document dealing with guidelines for diagnostic radiology and nuclear medicine. The 2008 published version is based on material developed around 2003, and is already under revision. These guidelines and/or criteria and their application in practice are further discussed in the subsections of Sections 2 and 4–7 on justification. Care has to be taken with their application in practice to make sure that they are well adapted to the time and place in which they are used. Other examples of guidance include the appropriateness criteria developed by the American College of Radiology, and the referral guidelines produced in the United Kingdom [15, 17, 30, 31]. There is much variability in the extent to which these tools are implemented in practice.

TABLE 38. REFERRAL GUIDELINES FOR PAEDIATRIC IMAGES
(adapted from Ref. [28])

Clinical problem	Investigation (dose)[a]	Recommendation (grade)[b]	Comment
PAEDIATRICS			
X ray irradiation needs to be minimized in children, especially those with long term problems			
Central nervous system			
Congenital disorders	MRI (0)	Indicated (C)	Definitive examination for all malformations and avoids X ray irradiation. Ultrasound needs to be considered in neonates. 3-D CT may be needed for bone anomalies.
Abnormal head appearance: hydrocephalus, odd sutures	Ultrasound (0) Skull radiography (I)	Indicated (B) Specialized investigation (C)	Ultrasound indicated where anterior fontanelle is open and where sutures are closed and/or closing. MRI indicated for older children. (CT may be appropriate if MRI not available.)
Epilepsy	Skull radiography (I)	Not routinely indicated (B)	Poor yield.

TABLE 38. REFERRAL GUIDELINES FOR PAEDIATRIC IMAGES *(adapted from Ref. [28])* (cont.)

Clinical problem	Investigation (dose)[a]	Recommendation (grade)[b]	Comment
	MRI (0) or nuclear medicine (II)	Specialized investigation (C)	MRI usually more appropriate than CT. Ictal and inter-ictal SPECT also used to identify focus before surgery.
Deafness in children	CT (II) MRI (0)	Specialized investigation (C)	Both CT and MRI may be necessary in children with congenital and post-infective deafness.
Hydrocephalus: shunt malfunction	Plain radiography (I)	Indicated (B)	Plain radiography needs to include the whole valve system.
	Ultrasound (0) or MRI (0)	Indicated (B)	Ultrasound if practical; MRI in older children (or CT if MRI unavailable). Nuclear medicine used to evaluate shunt function.
Developmental delay: cerebral palsy	Cranial MRI (0)	Specialized investigation (B)	
Headaches	Skull radiography (I)	Not indicated routinely (B)	If persistent or associated with clinical signs, refer for specialized investigations.
	MRI (0) or CT (II)	Specialized investigation (B)	In children, MRI is preferable if available because of the absence of X ray irradiation.
Sinusitis	Sinus plain radiography (I)	Not routinely indicated (B)	Not indicated before 5 years of age as the sinuses are poorly developed; mucosal thickening can be a normal finding in children. A single under-tilted otitis media view may be more appropriate than the standard otitis media view, depending on the child's age.
Neck and spine			
Torticollis without trauma	Plain radiography (I)	Not indicated	Deformity is usually due to spasm with no significant bone changes. If persistent, further imaging (e.g. CT) may be indicated following consultation.
Back or neck pain	Plain radiography (I)	Indicated (B)	Back pain without a cause is uncommon in children. Follow-up is needed if infection is suspected.

TABLE 38. REFERRAL GUIDELINES FOR PAEDIATRIC IMAGES *(adapted from Ref. [28])* (cont.)

Clinical problem	Investigation (dose)[a]	Recommendation (grade)[b]	Comment
	Nuclear medicine (II)	Specialized investigation (B)	When pain continues and XRs are normal. Useful in painful scoliosis.
	MRI (0)	Specialized investigation (B)	MRI defines spinal malformations and excludes associated thecal abnormality. MRI can also demonstrate juvenile disc lesions.
Spina bifida occulta	Plain radiography (I)	Not indicated routinely (B)	A common variation and not in itself significant (even in enuresis). However, neurological signs would require investigation.
Hairy patch, sacral dimple	Plain radiography (I)	Not indicated routinely (B)	May be helpful in older children.
Musculoskeletal examinations			
Non-accidental injury: child abuse	Plain radiography (I) of affected parts	Indicated (B)	Local policies will apply; close clinical and/or radiological liaison essential. Skeletal survey for those under 2 years of age after clinical consultation. May occasionally be required in the older child. CT/MRI of brain may be needed, even in the absence of cranial apparent injury.
	Nuclear medicine (II)	Indicated (B)	Sensitive for occult spine and/or rib fracture.
Limb injury: opposite side for comparison	Plain radiography (I)	Not indicated routinely (B)	Radiological advice needs to be sought.
Short stature, growth failure	Plain radiography (I) for bone age	Indicated at appropriate intervals (B)	2–18 years: left (or non-dominant) hand and/or wrist only. Premature infants and neonates: knee (specialized investigation). May need to be supplemented with a skeletal survey and MRI for hypothalamus and pituitary fossa (specialized investigations).

TABLE 38. REFERRAL GUIDELINES FOR PAEDIATRIC IMAGES *(adapted from Ref. [28])* (cont.)

Clinical problem	Investigation (dose)[a]	Recommendation (grade)[b]	Comment
Irritable hip	Ultrasound (0)	Indicated (B)	Ultrasound will delineate effusions which can be aspirated for diagnostic and therapeutic purposes. Plain radiography can be delayed but has to be considered when the symptoms are persistent. Nuclear medicine or MRI need to be considered when Perthes' disease is suspected and plain radiography is normal.
Limp	Plain radiography pelvis (I)	Indicated (C)	Gonad protection is routinely used unless shields will obscure the area of clinical suspicion. If slipped epiphyses is likely, lateral plain radiography of both hips is needed.
	Ultrasound (0) or nuclear medicine (II) or MRI (0)	Specialized investigation (B)	According to local policy, expertise and availability.
Focal bone pain	Plain radiography (I) and ultrasound (0)	Indicated (B)	Plain radiography may be normal initially. Ultrasound can be helpful, particularly in osteomyelitis.
	Nuclear medicine (II) or MRI (0)	Specialized investigation (B)	Increasing use of MRI here.
Clicking hip — dislocation	Ultrasound (0)	Indicated (B)	Plain radiography may be used to supplement ultrasound examination or where expertise is not available. Plain radiography is indicated in the older infant.
Osgood–Schlatter's disease	Plain radiography knee (I)	Not indicated routinely (C)	Although bony radiological changes are visible in Osgood–Schlatter's disease, these overlap with normal appearances. Associated soft tissue swelling needs to be assessed clinically rather than radiographically.

TABLE 38. REFERRAL GUIDELINES FOR PAEDIATRIC IMAGES
(adapted from Ref. [28]) (cont.)

Clinical problem	Investigation (dose)[a]	Recommendation (grade)[b]	Comment
Cardiothoracic examinations			
Acute chest infection	Chest radiography (I)	Not indicated routinely (C)	Initial and follow-up films are indicated in the presence of persisting clinical signs or symptoms, or in the severely ill child. The need for chest radiography is considered in fever of unknown origin. Children may have pneumonia without clinical signs.
Recurrent productive cough	Chest radiography (I)	Not indicated routinely (C)	Children with recurrent chest infection tend to have normal chest radiographs (apart from bronchial wall thickening). Routine follow-up chest radiography not indicated unless collapse present on initial chest radiography. Suspected cystic fibrosis requires specialist referral.
Inhaled foreign body (suspected)	Chest radiography (I)	Indicated (B)	History of inhalation often not clear. Bronchoscopy is indicated, even in the presence of a normal chest radiograph. Nuclear medicine/CT may be helpful to show subtle air trapping. Wide variation in local policy about expiratory films, fluoroscopy, CT and nuclear medicine (ventilation scintigraphy).
Wheeze	Chest radiography (I)	Not indicated routinely (B)	Children with asthma usually have a normal chest radiograph apart from bronchial wall thickening. Chest radiography indicated for sudden unexplained wheeze — may be due to inhaled foreign body (above).
Acute stridor	Plain radiography neck (I)	Not indicated routinely (B)	Epiglottitis is a clinical diagnosis but foreign body needs to be considered (above).
Heart murmur	Chest radiography (I)	Not indicated routinely (C)	Specialist referral may be needed; cardiac ultrasound may often be indicated.

TABLE 38. REFERRAL GUIDELINES FOR PAEDIATRIC IMAGES
(adapted from Ref. [28]) (cont.)

Clinical problem	Investigation (dose)[a]	Recommendation (grade)[b]	Comment
Gastrointestinal examinations			
Intussusception	Abdominal radiography (II)	Indicated (C)	Local policies require close paediatric, radiological and surgical liaison. Where expertise is available, both ultrasound and contrast enema (air or barium) can confirm diagnosis and guide reduction.
	Further imaging	Specialized investigation (B)	
Swallowed foreign body	Abdominal radiography (II)	Not indicated routinely (C)	Except for sharp or potentially poisonous foreign bodies, e.g. batteries.
	Chest radiography (I) (including neck)	Indicated (C)	If there is doubt whether the foreign body has passed, an abdominal radiograph after 6 days may be indicated.
Minor trauma to abdomen	Abdominal radiography (II)	Not indicated routinely (C)	Ultrasound may be used as initial investigation but CT is more specific, particularly in visceral trauma. Plain radiography may show bone injury in severe trauma. The principles for the investigation of major trauma in children are similar to those in adults.
Projectile vomiting	Ultrasound (0)	Indicated (A)	Ultrasound can confirm the presence of hypertrophic pyloric stenosis, especially where clinical findings are equivocal.
Recurrent vomiting	Upper gastro-intestinal contrast study	Not indicated routinely (C)	This symptom covers a wide range from obstruction in the neonatal period to reflux, posseters and children with migraine. Ultrasound may be helpful to confirm malrotation. However, upper gastrointestinal contrast studies may be indicated to exclude malrotation even with normal abdominal plain radiography. Contrast studies in neonates need to be undertaken as a specialized investigation. Nuclear medicine needs to be considered for gastric emptying and gastro-oesophageal reflux.

TABLE 38. REFERRAL GUIDELINES FOR PAEDIATRIC IMAGES
(adapted from Ref. [28]) (cont.)

Clinical problem	Investigation (dose)[a]	Recommendation (grade)[b]	Comment
Persistent neonatal jaundice	Ultrasound (0) Nuclear medicine (II)	Indicated (B) Indicated (B)	Early (<10 weeks) and prompt investigation is essential. The absence of dilatation in the intrahepatic bile duct does not exclude an obstructive cholangiopathy.
Rectal bleeding	Nuclear medicine (II)	Specialized investigation (B)	If Meckel's diverticulum is a possibility, nuclear medicine needs to be used first. Small bowel contrast studies may also be necessary. Nuclear medicine is also useful for investigation of inflammatory bowel disease. Endoscopy is preferable to barium enema for assessment of polyps and inflammatory bowel disease. Ultrasound can be used to diagnose duplication cysts.
Constipation	Abdominal radiography (II)	Not indicated routinely (C)	Many normal children show extensive faecal material; it is impossible to assess the significance of radiological signs. Nevertheless, abdominal radiography can help specialists in refractory cases.
	Contrast enema	Not indicated routinely (B)	If Hirschsprung's disease is suspected, specialist referral plus biopsy is preferred to radiological studies.
Palpable abdominal and/or pelvic mass	Ultrasound (0) and abdominal radiography (II)	Indicated (B)	If malignancy is suspected, further imaging needs to be performed in a specialized centre.
Uroradiology examinations			
Enuresis	Imaging	Not indicated routinely (B)	Ultrasound and urodynamic studies may be needed in cases of persistent enuresis.
Continuous wetting	Ultrasound (0)	Indicated (B)	Both examinations may be needed to evaluate the duplex system with an ectopic ureter.
	Intravenous urogram (II)	Indicated	

TABLE 38. REFERRAL GUIDELINES FOR PAEDIATRIC IMAGES *(adapted from Ref. [28])* (cont.)

Clinical problem	Investigation (dose)[a]	Recommendation (grade)[b]	Comment
Impalpable testis	Ultrasound (0)	Indicated (B)	To locate inguinal testis. MRI may be helpful to locate an intra-abdominal testis but increasingly laparoscopy is the investigation of choice.
Antenatal diagnosis of urinary tract dilatation	Ultrasound (0)	Indicated (B)	Local protocols need to be established. Mild dilatation can normally be monitored by ultrasound. Low threshold for specialist referral.
Proven urinary tract infection	Imaging ultrasound (0) or nuclear medicine (II) or cystography	Specialized investigations (C)	There is wide variation in local policy. Much depends on local technology and expertise. Most patients may remain on prophylactic antibiotics pending the results of investigations. The age of the patient also influences decisions. There is much current emphasis on minimizing radiation dose; hence, abdominal radiography is not indicated routinely (calculi rare). Expert ultrasound is the key investigation in all imaging strategies at this age. Thereafter, nuclear medicine provides data about renal structure (dimercaptosuccinic acid) and has virtually replaced the intravenous urogram here. Nuclear medicine will establish function, exclude obstruction and can also be used for cystography (direct or indirect) to show reflux. Formal direct plain radiography cystography is still needed in the young male patient (e.g. <2 years of age) where delineation of the anatomy (e.g. urethral valves) is critical.

[a] Effective dose classes: 0 (0 mSv); I (<1 mSv); II (1–5 mSv); III (5–10 mSv); IV (>10 mSv).

[b] A: randomized controlled trials, meta-analyses, systematic reviews; B: robust experimental or observational studies; C: other evidence where the advice relies on expert opinion and has the endorsement of respected authorities.

APPENDIX III

EXPLANATION OF TERMS AND ADDITIONAL DOSE DATA

III.1. EXPLANATION OF TERMS

Definitions of terms for health professionals and related information are provided below from the BSS [2].

medical physicist. A health professional, with specialist education and training in the concepts and techniques of applying physics in medicine, and competent to practise independently in one or more of the subfields (specialties) of medical physics.

Note: Competence of persons is normally assessed by the State by having a formal mechanism for registration, accreditation or certification of medical physicists in the various specialties (e.g. diagnostic radiology, radiation therapy, nuclear medicine). States that have yet to develop such a mechanism would need to assess the education, training and competence of any individual proposed by the licensee to act as a medical physicist and to decide, on the basis either of international accreditation standards or standards of a State where such an accreditation system exists, whether such an individual could undertake the functions of a medical physicist, within the required specialty.

medical radiation technologist. A health professional, with specialist education and training in medical radiation technology, competent to carry out radiological procedures, on delegation from the radiological medical practitioner, in one or more of the specialties of medical radiation technology.

Note: Competence of persons is normally assessed by the State by having a formal mechanism for registration, accreditation or certification of medical radiation technologists in the various specialties (e.g. diagnostic radiology, radiation therapy, nuclear medicine). States that have yet to develop such a mechanism would need to assess the education, training and competence of any individual proposed by the licensee to act as a medical radiation technologist and to decide, on the basis either of international standards or standards of a State where such a system exists, whether such an individual could undertake the functions of a medical radiation technologist, within the required specialty.

radiation protection officer. A person technically competent in radiation protection matters relevant for a given type of practice who is designated by the registrant, licensee or employer to oversee the application of relevant requirements.

radiological medical practitioner. A health professional with specialist education and training in the medical uses of radiation, who is competent to perform independently or to oversee procedures involving medical exposure in a given specialty.

Note: Competence of persons is normally assessed by the State by having a formal mechanism for registration, accreditation or certification of radiological medical practitioners in the given specialty (e.g. radiology, radiation therapy, nuclear medicine, dentistry, cardiology). States that have yet to develop such a mechanism need to assess the education, training and competence of any individual proposed by the licensee to act as a radiological medical practitioner and to decide, on the basis either of international standards or standards of a State where such a system exists, whether such an individual can undertake the functions of a radiological medical practitioner, within the required specialty.

referring medical practitioner. A health professional who, in accordance with national requirements, may refer individuals to a radiological medical practitioner for medical exposure.

III.2. ADDITIONAL DATA, RADIOGRAPHY

Table 39 provides a set of paediatric DRLs for Austria, based on a recent nationwide survey [158].

Table 40, from Borisova et al., provides information on ESD values obtained for a standard ‘5 year old patient’ in Bulgaria [70]. The ESD values are calculated from KAP and are compared with the 1996 EC reference values. Additional useful data, particularly for chest and abdominal ESD and KAP values, in a number of European centres, are also available in Smans et al. [71].

TABLE 39. AUSTRIAN DIAGNOSTIC REFERENCE LEVELS FOR COMMON X RAY EXAMINATIONS [158]

Examination	Age (a)	Incident air kerma (μGy)	Kerma area product (μGy · m^2)
Chest AP/PA	0	50	1.7
	1	60	2.3
	5	70	2.6
	10	90	3.7
	15	110	7.3
Skull AP/PA	0	350	15
	1	600	25
	5	750	35
	10	900	45
	15	1000	50
Skull lateral	0	300	10
	1	400	20
	5	500	25
	10	550	30
	15	600	35
Abdomen AP/PA	0	200	6
	1	300	9
	5	400	20
	10	750	50
	15	1000	70

Note: AP: antero-posterior; PA: postero-anterior.

III.3. AN APPROACH TO DIAGNOSTIC REFERENCE LEVELS ALLOWING FOR PATIENT THICKNESS

The following data from a Finnish study relate to uncertainty estimations, and the achievable accuracy of ESD and KAP determinations, which is close to 20%, in thoracic examinations in Finland (Fig. 1) [159]. This may be considered when comparing patient doses at a hospital with DRLs. Mean KAP and ESD ranged from 5 to 39 mGy · cm^2 and from 34 to 66 μGy in antero-posterior or postero-anterior, and from 8 to 109 mGy · cm^2 and 52 to 226 μGy in lateral projection, depending on patient thickness.

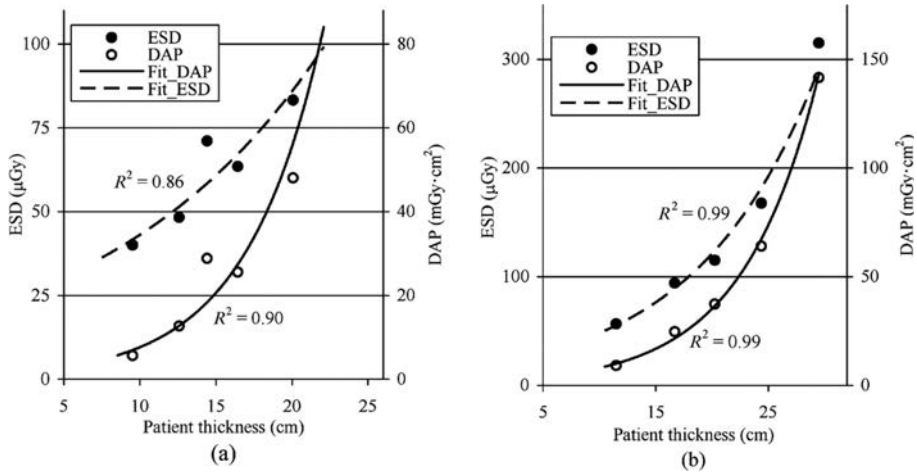


FIG. 1. Calculated third quartile values for entrance surface dose (ESD; solid circles) and dose–area product (DAP; open circles, i.e. kerma area product) in chest examinations as a function of patient thickness in: (a) antero-posterior or postero-anterior projections; (b) lateral projections (based on Ref. [159]).

TABLE 40. MEAN ENTRANCE SURFACE DOSE *(obtained from kerma area product measurements compared to European diagnostic reference levels in a 5 year old patient [70])*

Examination	Sample size	Entrance surface dose (μGy)	Diagnostic reference level (μGy)
Chest AP/PA	12	86	100
Micturating cystourethrogram	12	132	—
Intravenous urogram	6	608	900
Pelvis	3	996	1000
Skull	12	86	100

Note: AP: antero-posterior; PA: postero-anterior.

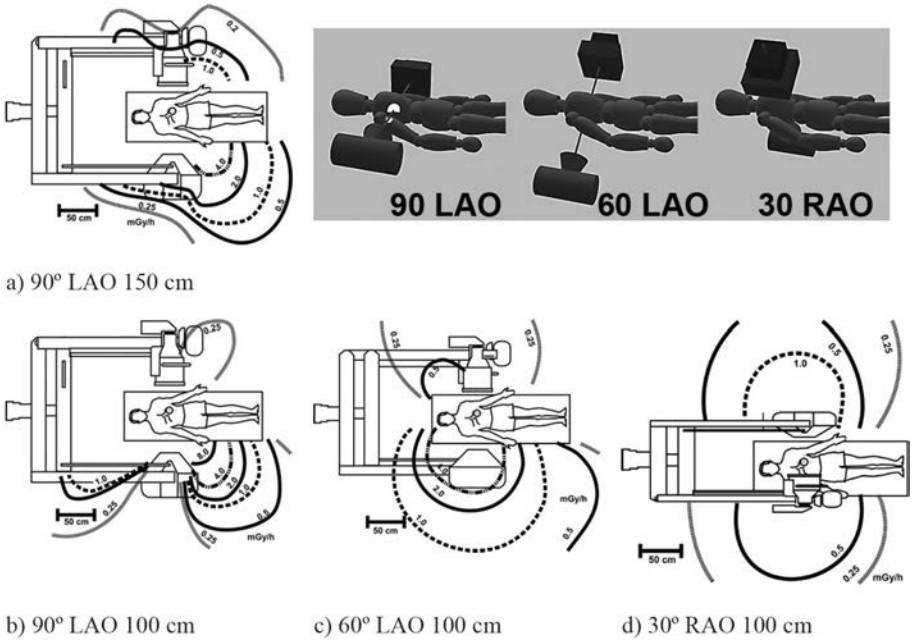
The method established by the National Radiological Protection Board (NRPB) of the United Kingdom for setting paediatric DRLs was not considered feasible in Finnish practice because of its complexity and the extra uncertainty introduced by the inexact match between conditions in Finland and those that prevailed for the NRPB [159, 160]. As exponential curve fitting for KAP and ESD values correlated well with patient thicknesses, a graphical method seems to be ideal for setting the DRLs when a sufficient number of patient dose measurements are not easily available. The Finnish Radiation and Nuclear Safety Authority has specified paediatric reference levels for thorax imaging in Finland by using exponential curves that are a function of patient thickness.

Appendix IV

DISTRIBUTION OF SCATTERED RADIATION IN ROOMS DESIGNED FOR SPECIAL AND INTERVENTIONAL PROCEDURES

Staff members have to position themselves strategically with respect to the configuration of the image receptor–X ray source assembly (Fig. 2). The operator generally needs to be on the image receptor side and, where possible, needs to step back during injections. The dominant direction for scatter tends to be from the patient backwards towards the X ray tube. This is well illustrated in the isodose diagrams in Fig. 2 [111].

It is important that operators become familiar with the profile of scattered radiation in the room with the tube oriented in the main directions used in practice. It is also worth being aware that if equipment has been designed and sold for interventional use that the suppliers, in compliance with international technical standards, have to provide isodose curves to the end user [50]. While Balter's data [111] are based on adults, they provide some guidance for paediatric intervention, pending the availability of more complete paediatric data.



a) 90º LAO 150 cm

b) 90º LAO 100 cm

c) 60º LAO 100 cm

d) 30º RAO 100 cm

FIG. 2. Typical scatter isodose curves for fluoroscopy systems for different projections [111]. LAO: left anterior oblique; RAO: right anterior oblique.

Appendix V

TECHNICAL FACTORS AND DOSE IN COMPUTED TOMOGRAPHY EXAMINATIONS

V.1. TECHNICAL APPROACHES TO DOSE REDUCTION

The following technical aspects of CT scanners are germane to dose reduction and the establishment of technical protocols for imaging. Support and help in this regard are available in the literature, from relevant web sites and from suppliers' representatives. Every effort has to be made to 'child-size' protocols [9, 10].

V.1.1. Tube output

In practice, dose reduction can be implemented by reducing the product of tube current and time (mAs). With all other factors held constant, patient dose is directly proportional to X ray tube current. For example, a 50% reduction in tube current results in a 50% decrease in radiation dose. However, the relationship between tube output and noise is more complicated. For example, a fourfold increase in output (and dose) improves the contrast or signal to noise ratio by a factor of up to two.

Many authors have demonstrated that the same photon flux at the detector can be achieved with children and adults while greatly reducing the mAs values with the children. At 120 kVp, Huda et al. reduced the current from 1300 mAs for a body weight of 120 kg to 200 mAs for 70 kg and 17 mAs for 10 kg [161]. Boone et al. reached a constant contrast to noise ratio for abdominal protocols when they decreased the current from 100% for a 28 cm thick adult phantom, to 56% for a 25 cm phantom, to 20% for a 20 cm phantom and to 5% for a 15 cm phantom [162].

Relatively low tube currents have been recommended for CT of the chest. Lucaya et al. were able to achieve high resolution CT with reduced dose (70–80%) and good quality lung images with 34 mAs in cooperative and 50 mAs in non-cooperative paediatric and young adult patients [163]. Rogalla et al. 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 [162].

A strategy recommended by several authors is to decrease baseline mA according to body diameter or body composition, and use the shortest rotation time available [9, 164–167]. This may be achieved by developing and using exposure charts of tube current settings based on patient weight or diameter at the anatomical regions of interest. Such charts allow the consideration of optimization of scan parameters in the axial plane.

Modern multidetector CT scanners generally have the facility for automatic tube current modulation, a form of AEC. Data for paediatric scanning have shown dose reductions of as much as 60% without any clinically significant loss of image quality with such systems [163–171].

Finally, it is important to be aware that one of the risks of low dose scanning in addition to the possibility of missing an important abnormality is a false positive finding that would not have occurred with a higher tube current and a lower noise level.

V.1.2. X ray tube voltage and filtration

The kVp needed to penetrate the body of a child is lower than that needed for an adult. In adult CT, 120 kVp is used, whereas 100 kVp and sometimes 80 kVp is adequate for children. Lowering the kVp will shift the physical interaction of ionizing radiation from Compton scatter towards the total absorption of the photoelectric effect, thereby enhancing contrast. This improves the low contrast that otherwise prevails in paediatric radiology owing to the lack of visceral fat [9, 73].

Lower kVp will also improve the contrast available from iodinated agents and can, thereby, enhance image quality. Excessive lowering of the kVp may cause artefacts [164] and, in practice, the use of 80 kVp is suggested for infants under 5 kg. This can sometimes be counterproductive and lead to excessive artefacts in these small infants when the chest or abdomen is being examined and the infant is breastfeeding [134]. A lower kVp may also, in some circumstances, decrease effective dose.

V.1.3. Slice thickness, scan length and pitch

Scan parameters need to be optimized for volume coverage by using representative volume sample(s) when the entire volume is not needed (by sequential scans with gaps). The maximal slice thickness appropriate for the specific diagnosis needs to be used. The table increment (axial scanning) or pitch (helical scanning) needs to be increased; where pitch is increased, the amount of radiation needed to cover the area of interest is decreased.

Thicker collimation with overlapping reconstruction needs to be used when thin slices are not needed. Additional, thick noise-reduced slices need to be reconstructed without an increase in exposure. Z axis dose modulation and/or noise-defined AEC will further contribute to dose reduction as they are more widely deployed. However, some newer scanners may automatically suggest or give effect to mA increases when the pitch is increased, and this could compromise potential dose reductions.

The minimum length required needs to be scanned, and one needs to be restrictive in defining upper and lower limits. Localizing projection scans extending just minimally beyond scan limits need to be used. Major overlap when scanning adjacent areas with different protocols needs to be avoided. In the case of multiphase scanning, a shorter scan length needs to be used for additional scans. The length of scans and fluoroscopy time in interventional applications need to be minimized. The minimum number of additional sequential functional scans needs to be used. Test bolus and/or bolus triggering needs to be replaced by a standard scan delay unless timing is very critical.

While the small dimension of a child requires thin slices to improve geometric resolution, using identical exposure with thinner slices will automatically increase noise. Keeping the noise level constant requires a more than proportional increase in the mAs and, thus, radiation exposure. Scanners with four detector rows are less dose efficient than single row detectors and need inappropriately high dose levels for thin slices. With 8–64 detector rows (and higher numbers), this phenomenon is less important [9].

V.1.4. Computed tomography detector technology

With single detector CT equipment, the radiation dose is approximately equal to the conventional contiguous transverse CT. Multidetector CT scanners use a slip-ring gantry, allowing spiral acquisition at rotation speeds as fast as 0.33 s for a full 360º rotation. The primary advantage of these scanners is the ability to scan more than one slice simultaneously and, hence, more efficient use of the radiation delivered from the X ray tube. The number of slices or data channels acquired per axial rotation continues to increase. Initial reports after the introduction of multidetector CT indicated increased doses to patients relative to single detector CT; more recent reports show comparable or decreased patient doses [171].

If the user selects settings identical to those used in single detector CT, there can be an increase in patient dose. Settings have to be determined appropriate to the specific scanner model. However, the issue is more complicated than the number of detector rows, as there have been other associated changes in technology such as improved detector efficiency, changes in the distance between the X ray tube and the isocentre, and image reconstruction technology which includes new filters, and these vary with the different equipment manufacturers. As with earlier stages of CT technology, there is potential for dose reduction but the actual dose reduction depends upon how the system is used.

It is important that the radiologist, medical physicists and CT system operators understand the relationship between dose to patients and image quality and be aware that often image quality in CT is greater than that needed for

diagnostic confidence. Objective measures such as image noise or contrast to noise ratio may not completely capture all of the features relevant to clinical image quality. Thus, determining 'optimal' image quality can be a complex task, as both quantitative metrics (e.g. noise) and subjective perceptions are involved.

AEC does not imply total freedom from operator selection of scan parameters. While CT systems without AEC require operator selection of mA or mAs, AEC systems require an understanding of newer concepts such as noise index, reference mAs and reference images, so that the AEC can operate effectively. Gaining an understanding of some parameters, such as the standard deviation of image pixels or a noise index, is not intuitive and entails opportunities for error.

Scanning parameters need to be based on study indication, patient size and the body region being scanned so that radiation dose can be adapted based on these parameters.

V.2. EFFECTIVE DOSE CALCULATION FROM DOSE LENGTH PRODUCT

Various approaches are used to calculate effective dose from DLP. One of the simplest is to use published conversion factors, which give normalized effective dose per unit DLP ($mSv \cdot mGy^{-1} \cdot cm^{-1}$). An example of such factors and the values over which they range for CT scans of head, neck, chest and abdomen and/or pelvis are provided in Table 41.

TABLE 41. CONVERSION FACTORS FROM DOSE LENGTH PRODUCT TO EFFECTIVE DOSE ($mSv \cdot mGy^{-1} \cdot cm^{-1}$) [138]

Age	Head	Neck	Chest	Abdomen and/or pelvis	Trunk
0	0.011	0.017	0.039	0.049	0.044
1 year old	0.0067	0.012	0.026	0.030	0.028
5 years old	0.0040	0.011	0.018	0.020	0.019
10 years old	0.0032	0.0079	0.013	0.015	0.014
Adult	0.0021	0.0059	0.014	0.015	0.015

Appendix VI

INSTRUCTIONS FOR THE CARE OF PAEDIATRIC PATIENTS FOLLOWING DIAGNOSTIC NUCLEAR MEDICINE EXAMINATIONS

The following is drawn from instructions for the care of paediatric patients following diagnostic nuclear medicine examinations issued by the Dublin Hospitals Group Risk Management Forum, Radiation Safety Standing Committee in March 2008. Minor edits have been made to generalize the approach.

VI.1. GENERAL REQUIREMENTS

Nursing instructions following nuclear medicine examinations ('the instructions') are to be adhered to by all staff caring for patients who have undergone nuclear medicine examinations.

It is the responsibility of the specialist radiographer in nuclear medicine to ensure that the instructions are provided to the nurse manager responsible for the patient's care.

The clinical nurse manager is responsible for ensuring that the instructions are entered into the patient's chart, and that the instructions follow the patient in case the patient is transferred from his or her care.

In the case of a patient from an external hospital attending for a nuclear medicine examination, it is the responsibility of the treating hospital to ensure that the instructions are provided to the individual responsible for the transfer of the patient to the external hospital.

It is then the responsibility of that individual to ensure that the instructions are provided to the clinical nurse manager responsible for the patient's care on arrival at the external hospital.

The hospital needs to ensure that there is a clear identifier system, so that all staff that may come into contact with the patient are notified of the need for following the instructions.

Examples of identifiers: a colour coded wristband, instructions at the head of the patient's bed, a label at the head of the patient's bed.

Instructions are to be observed until 09:00 the day after injection.

VI.2. VISITORS

All visitors may be asked to minimize close contact with the patient, and where possible remain at a distance of greater than 0.5 m (arm's length).

Pregnant visitors and/or children need to be discouraged, be asked to remain at a distance of greater than 0.5 m (arm's length) from the patient, and limit their visit to 30 min.

VI.3. STAFF

Unless the patient is fasting, they need to be encouraged to drink plenty of fluids, and empty their bladder frequently.

Standard hygiene procedures need to be used when handling urine bags, bottles, bedpans, nappies and soiled linen.

Linen and/or clothes soiled with urine need to be double bagged in alginate bags before storage in laundry bins and sending to the laundry.

Disposable nappies need to be placed in double plastic bags and disposed of through the general clinical waste stream.

Taking non-urgent blood samples needs to be postponed. Urgent blood samples may be taken after the imaging study is completed, and should be labelled as 'low level radioactive material, no personal hazard from handling'.

Non-urgent investigations and treatments need to be postponed for 6 h post-injection if they require staff to work in close contact (less than 0.5 m) with the patient for more than 30 min. In exceptional circumstances, clinical urgency may dictate otherwise — the medical physicist or clinical specialist needs to be contacted for specific advice (contact details for the relevant staff need to be provided here).

It is advised, as a precaution only, that pregnant women do not act as carers and comforters for such patients if the nursing care involves close contact (less than 0.5 m, arm's length) with the patient for more than 30 min.

It is advised, as a precaution only, to discourage children from playing with other children on wards or in dedicated areas.

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ISSN 1020–6450