Optimisation of protection in pediatric radiology

Claire-Louise Chapple.

Regional Medical Physics Department
Newcastle General Hospital, Westgate Rd
Newcastle upon Tyne, NE4 6BE, UK
claire.chapple@nuth.nhs.uk

Abstract

Over recent years there has been increasing concern over the level of radiation exposure to the population from diagnostic radiology, and this is particularly the case for paediatric radiology. In addition, many regulatory authorities place particular importance on the optimization of exposures to paediatric patients. This lecture aims to review and summarise the existing guidance for radiation protection in paediatric radiology and recent developments in technology and methodology. Guidelines on technique and dose in paediatric radiology have been produced by the CEC and by departments in the UK, among others, and these will be discussed along with the most recent surveys of radiation dose and diagnostic reference levels for paediatric patients. The varying attitudes to paediatric radiation protection between centres will be explored. There are a variety of equipment issues affecting dose reduction in paediatric radiology, and those to be discussed include tube filtration, automatic exposure control devices, anti-scatter grids and pulsed fluoroscopy. Choice of technique plays a big part in radiation dose, and exposure factors need to be scaled down for smaller patients. Other technique issues include neonatal chest/abdomen radiography, the use of a well collimated radiation beam and the use of lead shielding to protect radiosensitive organs. Optimization of computed tomography examinations for children is of particular concern, and some proposals for dose reduction will be presented and discussed. One of the most effective ways of reducing dose from an x-ray examination is to prevent the need for a repeat exposure – a common occurrence with scared or reluctant paediatric patients. Some practical suggestions and examples of easy measures that can be taken in this regard will conclude the lecture, along with a brief mention of the associated radiation protection issues for staff and carers involved in paediatric radiology.

1. Introduction

Diagnostic x-rays have been in use for over a hundred years and whereas their usefulness has never been in question, there is a growing awareness of the associated radiation risks both in the scientific and lay communities. In the UK, diagnostic radiology accounts for ninety percent of the UK population dose from man-made radiation (Fig 1), an average dose of 0.4 mSv per person [1] whereas in the USA this figure is likely to be around 3 mSv per person.

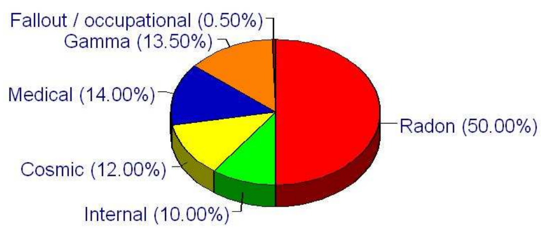

FIG 1. Average annual dose to the UK population from all sources (total 2.7 mSv)

Radiation protection is of particular concern in paediatric radiology for a number of reasons. Firstly, and most importantly, there is a greater chance for expression of radiation induced effects for children than for the adult population. Children are also usually considered to have greater sensitivity for certain types of cancer [2]. The most recent BEIR data [3] gives risk factors for children up to 10 times higher than those for adults, depending on the sex and irradiated organ, as shown in Table I. Another factor to consider is that some examinations are carried out with greater frequency for children. In particular, premature or sick neonates may receive a large number of x-ray examinations during the first few months of life and this can sometimes continue throughout early childhood. Finally, children will often be uncooperative during x-ray examination, thus requiring repeat or longer exposures.

Organ	Age at exposure					
	5		10		40	
	male	female	male	female	male	female
Stomach	65	85	55	72	27	35
Colon	285	187	241	158	122	79
Liver	50	23	43	20	21	10
Lung	261	608	216	504	104	240
Breast		914		712		141
Bladder	177	180	150	152	79	78
Thyroid	76	419	50	275	3	14
Leukemia	149	112	120	86	84	62
All cancers	1816	3377	1445	2611	648	886

Table I. Lifetime attributable risk of cancer incidence for selected organs (BEIRVII) (number of cases per 100,000 persons exposed to a single dose of 0.1Gy)

There has been much comment and discussion recently over the scale of the resultant risk to paediatric patients from diagnostic X-ray examinations, including the risk of a reduction in cognitive function due to low doses of radiation to the head [4] and the cancer risk resulting from paediatric computed tomography (CT) exposure in the US [5]. These highlight the importance of not only ensuring that all paediatric examinations are well justified, but also that they are performed with high regard to the radiation protection of the patient.

2. Review of doses in paediatric radiology

There have been a number of surveys carried out of radiation doses to paediatric patients undergoing diagnostic radiology examinations. These include assessment of entrance surface dose (ESD) and organ dose using either thermoluminescent dosimeters (TLDs) [6,7] or calculation methods [8]. Doses from simple fluoroscopy and interventional examinations, including cardiac procedures, have been assessed using dose-area product (DAP) measurements [9], and a large proportion of the work reported relates to doses from paediatric CT [10,11,12]. For a detailed analysis, the reader is referred to the work listed at the end of the manuscript..

One of the reasons that paediatric dosimetry, and in particular the derivation of reference doses, is difficult is because of the wide and continuous variation in patient size. A number of authors have considered this issue in some depth [13,14]. In spite of the problems, some reference doses have been produced both as part of the European quality criteria for paediatric radiology [15], which comprise ESDs, mostly for 5 yr old patients with some for newborns and infants, and as part of the 5 yearly review of the UK national patient dose database [16]. The latter gives suggested paediatric national reference doses, in terms of DAP, for barium meal, barium swallow and micturating cystogram examinations, for each of 5 age groups. Table III summarizes some of these reference doses along with locally derived reference doses (from two different years) for fluoroscopy examinations [17]. Only data for 5 yr old patients has been included in this table. The change in local reference doses reflects the switch to more modern equipment with dose-saving features. National (UK) reference doses for paediatric CT have been given by Shrimpton et al [18], and those for dose-length product (DLP) are summarized in Table III, along with previously published European dose levels [19].

Examination	European Ref. Doses: 1996 data (ESD)	UK National Ref. Doses : 2005 data (DAP)	Local Ref. Levels (DAP) - North of England 2007 data	1998 data
MCUG	-	0.8 Gycm^2	0.2 Gycm^2	1.4 Gycm^2
Barium Meal	-	1.2 Gycm^2	0.2 Gycm^2	2.1 Gycm^2
Barium Swallow	-	1.3 Gycm^2	0.4 Gycm^2	2.4 Gycm^2
Chest PA/AP	100 µGy	-	-	-
Chest Lat	200 µGy	-	-	-
Abdomen AP/PA	1000 µGy	-	-	-
Pelvis AP	900 µGy	-	-	-
Skull PA/AP	1500 µGy	-	-	-
Skull Lat	1000 µGy	-	-	-

Table II. European, national and local reference levels for radiographic & fluoroscopic examinations

Examination	Age	DLP (mGycm^2) European Doses (2000)	UK National Ref. Doses (2003)
Chest (detection of malignancy)	0-1 yr old	200	200
Chest (detection of malignancy)	5 yr old	400	230
Chest (detection of malignancy)	10 yr old	600	370
Head (trauma)	0-1 yr old	300	270
Head (trauma)	5 yr old	600	470
Head (trauma)	10 yr old	750	620

Table III. National reference doses and previous European doses for paediatric CT

3. Published guidelines in paediatric radiology

Guidelines have been published to address the issue of radiation protection and good practice in paediatric radiology, notably the European guidelines on quality criteria for diagnostic radiographic images in paediatrics [15]. These resulted from a European wide cooperation between various professionals and authorities involved in diagnostic radiology, and characterise a level of acceptability of basic radiographs, together with examples of good radiographic technique. Guidelines on best practice in the x-ray imaging of children have also been produced in the UK [20], including referral criteria for a number of examinations, examples of good radiographic technique, suggested exposure factors and a selection of child-friendly aids. Much of the content of these guidelines will be discussed in the following sections. Although the guidelines have been available for a number of years, there remains a wide variation in practice in paediatric radiology, even within a single country or region.

In a local UK survey [21], comprising 28 radiology departments in the north of England, 65% responding radiographers had not heard of the European Guidelines and although 85% departments had paediatric protocols in place, only a third of these were written with reference to the guidelines. The most common reason for not utilizing the guidelines was lack of awareness, although lack of time, lack of money and the small number of paediatric patients were also given as reasons. Regarding the implementation of particular recommendations, the majority of departments used exposure charts, immobilisation devices and distraction techniques, but very few had designated rooms or staff for paediatric radiology or any additional filtration on the X-ray equipment. These results are detailed in table IV.

Recommendation	Number of departments implementing
Designated room	3
Named staff	3
Lead protection	16
Immobilisation devices	13
Exposure charts	13
Extra filtration	2
Distraction techniques	14

Table IV. Results of survey on implementation of paediatric guidelines

These results highlight the importance of education in paediatric radiology. It is evident that, in the UK, there remains a lack of specialist training (outside of dedicated paediatric centres), often along with a lack of financial and managerial support for paediatric radiation protection. This is particularly the case where paediatric throughput is low and thus deemed to be of relatively low importance. The effects of the difference made by the level of staff training have been highlighted by Cook et al [22], and the situation is likely to be reflected worldwide.

4. Equipment

Ideally, paediatric patients would be imaged using dedicated equipment that has been designed and set up specifically for them. Although this may often not be possible, there are a number of factors to consider when selecting equipment for paediatric use. It is also important to ensure that equipment is subject to a rigorous programme of quality assurance, to ensure that features discussed below are working correctly.

4.1 Generators

As paediatric patients will often be uncooperative, short exposure times are essential for obtaining good quality images. To obtain short exposure times requires powerful generators and tubes with optimal rectification, as is the case for most modern generation equipment.

4.2 Filtration

Tube filtration removes the lower energy part of the X-ray beam spectrum that contributes to patient dose without contributing to the image. Most X-ray tubes will have inherent filtration of up to 2.5mm Al equivalent, but additional filtration will further reduce unnecessary patient dose. In addition, one of the problems in paediatric radiology can often be obtaining a sufficiently low output, particularly when using a high tube voltage (kV) technique. The use of a more heavily filtered beam allows a high kV technique to be used, even when the generator does not permit the very low exposure times desirable.

Many authors have studied a range of different filter materials, particularly the so-called k-edge filters such as erbium or gadolinium, with a view to obtaining an optimal X-ray spectrum with respect to both dose and image quality [23,24]. However, the consensus now is that such filters are no better than the much easier obtained aluminium or copper filters. The European guidelines recommend using an additional 1mm Al with 0.1mm or 0.2mm Cu.

Some modern X-ray equipment has the facility to vary filtration according to examination and for specific patients. This has advantages, particularly when the equipment is used for both adults and children, as additional filtration may not be optimal for all patients. Selection of an appropriate filter may be incorporated into set protocols, or may require manual adjustment for each patient. When this facility is not available, an additional filter may often be easily added manually. For under-couch tubes, where addition of a beam filter is not straightforward, one solution for infants has been to use a large copper sheet directly on the couch to provide the additional beam attenuation [25].

The use of additional filtration of 0.1/0.2mm Cu has been shown to reduce doses by up to 40% [26,27].

4.3 Anti-scatter grids

Anti-scatter grids reduce the amount of scattered radiation reaching, and thus degrading, the image, but also attenuate the beam thus requiring an increase in dose to the patient. For small patients, the amount of scatter produced is relatively small and an anti-scatter grid will usually be unnecessary. The equipment used should therefore have the facility of removing the grid. If an anti-scatter grid is required, for older or more obese children, then consideration should be given to the composition and grid ratio of the device, to keep doses as low as possible.

4.4 Automatic exposure control

Unless specifically designed for paediatric patients, automatic exposure control (AEC) devices are rarely appropriate for use in paediatric radiology. This is partly due to the size and positioning of the ionization chambers, which will usually cover too large an area, or an inappropriate area, of a child's body. In addition, such AEC devices are most often found attached to an anti-scatter grid, the use of which is often unnecessary when X-raying small children (as discussed above).

4.5 Low dose fluoroscopy

For fluoroscopy examinations, one of the most effective dose reduction measures available on equipment is the use of pulsed fluoroscopy. When available this should always be taken advantage of in paediatric examinations, using the lowest pulse rate acceptable to the operator. The use of last image hold, where the most recent image stays displayed on the screen, rather than disappearing from view once screening has stopped, is also a valuable tool in preventing unnecessary exposure. The dose reduction achievable using pulsed fluoroscopy compared to continuous fluoroscopy is in the order of 50% [28]. Grid-controlled pulsed fluoroscopy has also been used, together with a single frame grabbed image to replace pelvic radiography in children, with a dose reduction of 65-83% [29].

5. Choice of technique

Choice of equipment for paediatric radiology may often be limited by financial or other constraints, but many aspects relating to technique can be applied by anyone who has been educated in them.

5.1 Selection of technique factors

Paediatric radiology involves X-raying patients varying in size from a tiny newborn up to full adult size, and so the correct selection of technique factors such as kV and mAs is not straightforward, particularly when AEC devices are not usable, as discussed above. The best, and simplest, method is to use exposure charts, based on weight rather than age in most cases that have been derived from experience on the particular equipment in use. Modern equipment may have preset exposure factors, but these may often only be for a small number of arbitrary sizes and may not necessarily represent optimal exposures. Particular care needs to be taken when selecting exposure factors for Computed radiography (CR) and digital radiography (DR) systems as there is not the same negative feedback from overexposure as there is with film-screen systems, and an upward creep in exposure factors is often reported [30].

5.2 Collimation

Good collimation, i.e. restricting the field-size to the area of interest only, is of great importance in paediatric radiology as with increasingly small patient size radiosensitive organs in the body will lie closer together. Good collimation can be difficult, as it requires accurate positioning of the patient and for them to remain still, along with good knowledge of paediatric anatomy and pathology. This is one reason why it is recommended that only well trained, preferably dedicated, staff undertake paediatric radiology. Poor collimation is a frequent observation of paediatric technique audit [22]. For radiography of neonates in special care baby units it is recommended that the beam be further delineated by strips of lead placed on top of the incubator [31].

5.3 Lead shielding
Lead shielding is recommended for radiosensitive organs such as the gonads, eyes and thyroid where appropriate. This will be for examinations in which the organs are just outside the primary beam and may receive a high dose from scattered or extra-focal radiation or, in some instances, where the organs are inside the primary beam but may be shielded without obscuring information in the image. It is, however, important that any shielding used is positioned correctly as otherwise it might at best be ineffectual or, at worst, cause a radiograph to require repeating.

5.4 Choice of projection
One of the easiest ways to reduce dose to radiosensitive organs is to ensure that they are shielded by the rest of the body i.e. by selecting PA projection for chests and spine radiographs to reduce breast dose and PA rather than AP projection in skull radiography to reduce eye dose. For chest radiography, use of a wall bucky and an erect projection when a child is able to sit or stand allows a longer focus-skin-distance (FSD) to be employed, which reduces the dose when the minimum mAs has been set, in addition to the clinical benefits. It should be remembered that for a similar size child requiring a supine chest view (at a shorter FSD), the mAs would need to be reduced to achieve the same dose.

5.5 Neonatal radiography
It is common for neonates to require both chest and abdomen radiographs, and for a choice to be made between taking these separately or as a single whole trunk shot. It is recommended that a single view should only be used for babies of less than 1000g, and that the beam should then be centred on the chest area, with lead shielding used to protect the baby's head. This avoids foreshortening of the chest. For larger neonates, separate well-collimated views should be taken of the chest and abdomen.

For radiographs to check the positioning of umbilical arterial/umbilical venous catheters, a single view should be use with lead defining the area of interest, as illustrated in figure 2.

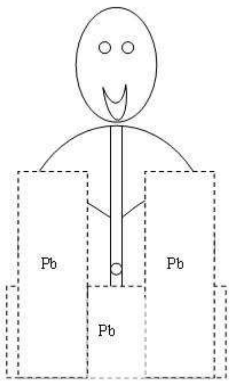

FIG 2: Recommended lead placement for UAC/UVC positioning

6. Computed Tomography

Computed Tomography (CT) is probably the area of greatest importance for radiation protection purposes, due to the high doses involved and its escalating use. In 2002, 47% of the UK population dose from diagnostic radiology came from CT (having risen from 40% in 1998), even though it represented only 7% of examinations and this figure is likely to have increased since then. In the US there has been much recent concern over the level of referrals for paediatric CT examinations and the doses received during them [5].

Most of the points made in the preceding sections apply equally well to CT. However, they are probably less likely to be applied. It is common, for instance, for adult exposure factors to be only slightly reduced, if at all, for paediatric patients. This situation is being improved by the increasing prevalence of dose modulated CT systems which should automatically reduce factors for smaller patients, although there is little numerical data available to date to demonstrate this. It has been proposed that, where dose modulation is not available, a simple attenuation model can be used to provide the framework for paediatric CT factor selection on the basis of keeping a constant level of noise in the image [32].

The issue of shielding in CT has mostly been restricted to investigations into the use of bismuth shields for breast or eyes in the primary beam [33, 34], which have been shown to reduce the relevant doses by 30-40%. However, recent work has shown that small children receive a significant external scatter dose from CT examinations, particularly for larger beam widths, which can be shielded. In head CT of neonates and infants, significant dose reduction was achieved by the use of lead shielding around the trunk. A reduction in up to 30% in effective dose was obtained, along with reductions in dose to thyroid and breast tissue of up to 30% and 70% respectively. Such shielding is now in routine clinical practice in several local hospitals thus reducing the radiation risks to infants and neonates from CT examination of the head [35].

7. Environment

Preventing the need for re-takes of radiographs, or extended screening examinations is the best way to reduce unnecessary radiation dose. One of the chief factors influencing this is the non-cooperation of a frightened child, often accompanied by worried and ill-informed parents. There are many very simple and mostly low cost ways of making the environment as child friendly and distracting as possible, including:

- Separate waiting area for children with suitable decoration and toys etc
- Pictures/murals in X-ray room
- Hanging/musical toys on equipment
- Patterned lead aprons for staff and carers
- Availability of CDs/DVDs for screening examinations

Other useful ideas are to have familiar flavours to put in contrast agent drinks; certificates, stickers and lollipops as rewards; and, most importantly, to take time to relax the child and explain things to them (if old enough) and to their parents who can then provide effective help in conducting the examination. It is worth noting that, in rooms used by both adult and paediatric patients, the adult patients are often also appreciative of the decorations!

8. Radiation protection for staff and carers

Radiographic and nursing staff, along with patient carers will often be closely involved in paediatric examinations, and of necessity be in proximity to the beam. In general, all measures taken to reduce patient dose will also reduce the scattered dose to other people in the controlled area. However, some extra points are worth noting. It is important that anyone involved in restraining a child understands clearly what their role is and how best to perform it. They should be given suitable PPE (lead apron and gloves if necessary) and on no account should any part of their body enter the primary beam. It should also be checked that any female providing such restraint is not pregnant. In general, radiographic staff should not be involved in providing manual restraint, nor should a single member of nursing staff fulfil the role repeatedly. Use should be made of restraining aids where possible, and their use explained to carers.

9. Conclusions

The importance of radiation protection in paediatric radiology is indisputable, and there is considerable published guidance to assist in this. Where possible, equipment should be selected and optimised for X-raying children, making use of any available dose-reduction features, and technique should be adapted to the size of the patient, with good collimation and use of shielding. The patient environment should be made as welcoming to children as possible, and time taken to get the procedure right the first time. The most important factor in paediatric radiation protection remains the education of the radiographers and radiologists responsible for their care.

References

1. Watson SJ, Jones AL, Oatway WB, Hughes JS, *Radiation exposure of the UK population – 2005 review*. HPA-RPD-001(2005).
2. Stather JW, Muirhead CR, Edwards AA, Hamson JD, Lloyd DC, Wood NR, *Health effects developed from the 1988 UNSCEAR report*. National Radiological Protection Board Report, NRPB-R226 (HMSO, London) (1988).
3. BEIR VII Phase 2: *Health risks from exposure to low levels of ionising radiation*, National Academies Press, Washington (2005).
4. Hall P, Adami H-O, Trichopoulos D, Pedersen NL, Lagiou P, Ekbom A, Ingvar M, Lundell M, Granath F, *Effect of low doses of ionising radiation in infancy on cognitive function in adulthood: Swedish population based cohort study*. BMJ 328:19 (2004).
5. Brenner D, Elliston C, Hall E, Berdon W, *Estimated risks of radiation-induced fatal cancer from paediatric CT.* AJR Am J Roentgenol, 176(2) p289-96 (2001).
6. Gogos KA, Yakoumakis EN, Tsalafoutas IA, Makri TK, *Radiation dose considerations in common paediatric examinations*. Paediatr Radiol, 33(4) p236-40 (2003).
7. Sulieman A, Theodorou K, Vlychou M, Topaltzikis T, Kanavou D, Fezoulidis I, Kappas C *Radiation dose measurement and risk estimation for paediatric patients undergoing micturating cystourethrography*. Br J Radiol 80(957):731-7 (2007).
8. Mohamadain KE, de Rosa LA, Azevado AC, Guebel MR, Boechat MC, Habani F, *Dose evaluation for paediatric chest x-ray examinations in Brazil and Sudan: low doses and reliable examinations can be achieved in developing countries.* Phys Med Biol, 49(6) p1017-31 (2004).
9. Martinez LC, Vano E, Gutierrez F, Rodriguez C, Gilarranz R, Manzanas MJ, *Patient doses from fluoroscopically guided cardiac procedures in pediatrics*. Phys Med Biol 21;52(16):4749-59 (2007).
10. Huda W, Vance A., *Patient radiation doses from adult and pediatric CT*. AJR Am J Roentgenol 188(2):540-6 (2007).
11. Lee C, Lee C, Staton RJ, Hintenlang DE, Arreola MM, Williams JL, Bolch WE, *Organ and effective doses in pediatric patients undergoing helical multislice computed tomography examination*. Med Phys 34(5):1858-73 (2007).
12. Fujii K, Aoyama T, Koyama S, Kawaura C, *Comparative evaluation of organ and effective doses for paediatric patients with those for adults in chest and abdominal CT examinations*. Br J Radiol 80(956):657-67 (2007).
13. Chapple C-L, Broadhead DA, Faulkner K, *A phantom based method from deriving typical patient doses from measurements of dose-area product on populations of patients*. Br J Radiol, 68,1083-1086 (1995).
14. Hart D, Wall BF, Shrimpton PC, Bungay DR, and Dance D, *Reference doses and patient size in paediatric radiology*. Chilton, NRPB-R318 (2000).
15. European Commission, *European guidelines on quality criteria for diagnostic radiographic images in paediatrics*, Report EUR 16261, Luxembourg: Office for Official Publications of the European Communities (1996).
16. Hart D, Hillier MC, Wall BF, *Doses to patients from radiographic and fluoroscopic X-ray imaging procedures in the UK – 2005 review*. Chilton, HPA-RPD-029 (2007).
17. C-L Chapple, DA Broadhead, K Faulkner. *Reference doses for paediatrics from fluoroscopy procedures*. Rad Prot Dosim, 1998:80,1-3;203-206.
18. Shrimpton PC, Hillier MC, Lewis MA, Dunn M, *Doses from computed tomography (CT) examinations in the UK – 2003 review*. Chilton, NRPB-W67.
19. Shrimpton PC, Wall BF,.*Reference doses for paediatric computed tomography*. Radiat Prot Dosim 90 1-2 249-252 (2000).
20. Cook JV, Shah K, Pablot S, Kyriou J, Pettet A, Fitzgerald M, *Guidelines on best practice in the X-ray imaging of children*. London: St George's Hospital & St Helier Hospital (1998).

21. Chapple C-L, Hunter E, *Dose reduction in paediatric radiology*. BIR meeting: Dose reduction in diagnostic radiology (revisited). London, 2004.
22. Cook JV, Kyriou JC, Pettet A, Fitzgerald MC, Shah K, Pablot SM, *Key factors in the optimization of paediatric X-ray practice*. Br J Radiol, 74(887)p1032 (2001).
23. Cranage RW, Howard CJ, Welsh AD, *Dose reduction by the use of erbium filtration in a general radiographic room*. Br J Radiol, 65 232-237 (1992).
24. Shrimpton PC, Wall BF, Fisher ES, *The influence of tube filtration and potential on patient dose during X-ray examinations*. Phys Med Biol 33(10) 1205-1212 (1988).
25. Chapple C-L**,** *Optimisation of paediatric radiation dose using additional beam filtration.* Institution of Physics and Engineering in Medicine and Biology Meeting, Royal Marsden Hospital, London. 3rd November 1999.
26. Fenner JW, Morrison GD, Kerry J, West N, *A practical demonstration of improved technique factors in paediatric fluoroscopy.* British Journal of Radiology 75 596-602 (2002).
27. Hansson B, Finnbogason T, Schuwert P, Persliden J, *Added copper filtration in digital paediatric double-contrast colon examinations: effects on radiation dose and image quality.* Eur Radiol 7(7):1117-22 (1997).
28. Hernandez RJ, Goodsitt MM, *Reduction of radiation dose in pediatric patients using pulsed fluoroscopy*. Am J of Roent 167, 1247-1253, (1996).
29. Waugh R, McCallum HM, McCarty M, Montgomery R, Aszkenasy M, *Paediatric pelvic imaging: optimisation of dose and technique using digital grid-controlled pulsed fluoroscopy*. Paediatr Radiol 31 368-373 (2001).
30. Warren-Forward H, Arthur L, Hobson L, Skinner R, Watts A, Clapham K, Lou D, Cook A, *An assessment of exposure indices in computed radiography for the posterior–anterior chest and the lateral lumbar spine*. Br J Radiol 80**,** 26-31 (2007).
31. Faulkner K, Barry JL, Smalley P, *Radiation dose to neonates on a special care baby unit*. Br J Radiol 62, 230-233 (1989).
32. Kotre CJ, Willis SP, *A method for the systematic selection of technique factors in paediatric CT*. Br J Radiol 76**,** 51-56 (2003).
33. Yilmaz MH, Albayram S, Yasar D, Ozer H, Adaletli I, Selcuk D, Akman C, Altug A, *Female breast radiation exposure during thorax multidetector computed tomography and the effectiveness of bismuth breast shield to reduce breast radiation dose*. J Comput Assist Tomogr 31(1):138-42 (2007).
34. Perisinakis K, Raissaki M, Theocharopoulos N, Damilakis J, Gourtsoyiannis N, *Reduction of eye lens radiation dose by orbital bismuth shielding in pediatric patients undergoing CT of the head: a Monte Carlo study*. Med Phys 32(4):1024-30 (2005).
35. Chapple C-L, Willis J, Shemilt A. *Dose reduction in paediatric head computed tomography examinations*. Abstract: Proceedings of the Seventh SRP International Symposium 2005; 187-192.

Bibliography

Bacher K, Bogaert E, Lapere R, De Wolf D, Thierens H. *Patient-specific dose and radiation risk estimation in pediatric cardiac catheterization*. Circulation 111(1):83-9 (2005).

Brisse HJ, Madec L, Gaboriaud G, Lemoine T, Savignoni A, Neuenschwander S, Aubert B, Rosenwald JC, *Automatic exposure control in multichannel CT with tube current modulation to achieve a constant level of image noise: experimental assessment on pediatric phantoms* ed Phys 34(7):3018-3 (2007).

Brown PH, Thomas RD, Silberberg PJ, Johnson LM, *Optimization of a fluoroscope to reduce radiation exposure in pediatric imaging.* Pediatr Radiol 30(4) 229-35 (2000).

Chapple CL, Willis S, Frame J. *Effective dose in pediatric CT*. Phys Med Biol; 47:107 –115 (2000).

Chodick G, Ronckers CM, Shalev V, Ron E, *Excess lifetime cancer mortality risk attributable to radiation exposure from computed tomography examinations in children*. Isr Med Assoc J 9(8):584-7 (2007).

Cook JV, *Radiation protection and quality assurance in paediatric radiology* Imaging 13(4): 229 – 238 (2001).

Coursey C, Frush DP, Yoshizumi T, Toncheva G, Nguyen G, Greenberg SB. *Pediatric chest MDCT using tube current modulation: effect on radiation dose with breast shielding*. AJR Am J Roentgenol 190(1):W54-61 (2008).

de Gonzalez AB, Kim KP, Samet JM. *Radiation-induced cancer risk from annual computed tomography for patients with cystic fibrosis*. Am J Respir Crit Care Med 176(10):970-3 (2007).

Donnelly LF, Reducing radiation dose associated with pediatric CT by decreasing unnecessary examinations. Am J Roentgenol 184(2) 655-7 (2005).

Frush DP, Donnelly LF, Rosen NS, *Computed tomography and radiation risks: what pediatric health care providers should know*. Pediatrics 112(4) 951-7 (2003).

Goske MJ, Applegate KE, Boylan J, Butler PF, Callahan MJ, Coley BD, Farley S, Frush DP, Hernanz-Schulman M, Jaramillo D, Johnson ND, Kaste SC, Morrison G, Strauss KJ, Tuggle N *The 'Image Gently' campaign: increasing CT radiation dose awareness through a national education and awareness program*. Pediatr Radiol 38(3) 265-9 (2008).

Hollingsworth C, Frush DP, Cross M, Lucaya J, *Helical CT of the body: a survey of techniques used for pediatric patients*. Am J Roentgenol 180(2) 401-6 (2003).

Hollingsworth CL, Yoshizumi TT, Frush DP, Chan FP, Toncheva G, Nguyen G, Lowry CR, Hurwitz LM, *Pediatric cardiac-gated CT angiography: assessment of radiation dose*. AJR Am J Roentgenol 189(1):12-8 (2007).

International Commission on Radiological Protection. *Radiation and your patient: a guide for medical practioners*. Ann ICRP 31(4) 5-31 (2001).

Lu ZF, Nickoloff EL, Ruzal-Shapiro CB, So JC, Dutta AK, *New automated fluoroscopy systems for pediatric applications*. J Appl Clin Med Phys 6(4) 88-105 2005.

Mansson LG, Bath M, Mattsson S, *Priorities in optimisation of medical X-ray imaging--a contribution to the debate*. Radiat Prot Dosimetry 114(1-3):298-302 (2005).

Mazonakis M, Tzedakis A, Damilakis J, Gourtsoyiannis N, *Thyroid dose from common head and neck CT examinations in children: is there an excess risk for thyroid cancer induction?* Eur Radiol 17(5):1352-7 (2007).

Minigh J, *Pediatric radiation protection*, Radiol Technol 76(5) 365-75 (2005).

Perisinakis K, Raissaki M, Damilakis J, Stratakis J, Neratzoulakis J, Gourtsoyiannis N. *Fluoroscopy-controlled voiding cystourethrography in infants and children: are the radiation risks trivial?* Eur Radiol 16(4):846-51 (2006).

Paterson A, Frush DP, *Dose reduction in paediatric MDCT: general principles*. Clin Radiol 62(6):507-17 (2007).

Roebuck DJ, *Risk and benefit in pediatric radiology*. Paediatr Radiol 29(8) 637-40 (1999).

Saxena AK, Prasad K, Kaza RK, *Reducing radiation dose to pediatric patients*. Am J Roentgenol 185(6) 1658 (2005)

Sikand M, Stinchcombe S, Livesley PJ, *Study on the use of gonadal protection shields during paediatric pelvic X-rays*. Ann R Coll Surg, 85 (6) p422-5 (2003).

Strauss KJ, Kaste SC, *ALARA in paediatric interventional and fluoroscopic imaging: striving to keep radiation dose as low as possible furing fluoroscopy of pediatric patients – a white paper executive summary*. J Am Coll Radiol 3 (9) p686-8 (2006).

Theocharopoulos N, Damilakis J, Perisinakis K, Tzedakis A, Karantanas A, Gourtsoyiannis N, *Estimation of effective doses to adult and pediatric patients from multislice computed tomography: A method based on energy imparted*. Med Phys 33(10):3846-56 (2006).

Thomas KE, Parnell-Parmley JE, Haider S, Moineddin R, Charkot E, Brn David G, Krajewski C, *Assessment of radiation dose awareness among pediatrician*s. Pediatr Radiol, 36(8) 823-32 (2006).

Toma P, *Radiation safety in children: what we should know*. Radiol Med 105(1-2) 83-91 (2003).