REVIEW

The radiation burden of radiological investigations

W Mazrani, K McHugh, P J Marsden

Arch Dis Child 2007;**92**:1127–1131. doi: 10.1136/adc.2006.101782

The harmful effects of ionising radiation are widely acknowledged. It has been reported that young children, particularly girls, have a higher sensitivity to radiation than adults. However, the exact detrimental effects of radiation, particularly at the low doses used in routine diagnostic radiography, are unknown and the subject of much controversy. Computed tomography (CT) accounts for about 9% of all radiological examinations but is responsible for 47% of medical radiation dose. Approximately 11% of CT examinations performed are in the paediatric population, but the long-term hazards of CT are unknown.

Ionising radiation takes the form of electromagnetic radiation (eg, *x* or gamma rays) or energetic particles (eg, alpha, beta, protons and neutrons). Natural sources of ionising radiation include radon gas (which accounts for approximately 55% of the UK average background radiation) and cosmic rays (8%).[1] This background radiation contributes an approximately 2.6-mSv dose per person per year in the UK. A linear, no threshold (LNT) extrapolation of the dose–response relationship from high to low doses implies that even such low levels of radiation exposure will induce several thousand fatal cancers annually. Up to 5000 deaths per year in the UK may be radiation-induced or associated, with up to 5% of lung cancers attributable to radon in adults.[1]

The use of ionising radiation in medicine accounts for 15% of the total radiation burden.[2] The single largest source of ionising medical radiation is the *x* ray, which was discovered by Roentgen in 1895. Within months of their discovery it was apparent that *x* rays had the potential to cause somatic damage to tissue. These deterministic effects (table 1) are not a major consideration in diagnostic radiology but larger doses are relevant to children who undergo radiotherapy, usually for childhood cancer. A few years after therapy stochastic effects (table 1), and in particular a relationship with cancer, may become apparent.

The single greatest resource on the effects of radiation on humans has been the data from the survivors of the atomic bombs dropped on Japan in 1945. The risk of fatal cancer induction is estimated at 5% per Sievert averaged over the entire population.[3] The LNT model suggests that this is also the excess relative risk for cancer mortality that individuals who are undergoing computed tomography (CT) at present, will experience in years to come. According to the data from the Radiation Effects Research Foundation, approximately 35 000 people (75% of the survivors) exposed to radiation from the nuclear bombs in Japan received doses in the range of 0.005–0.2 Sv.[4]

Younger subjects and in particular girls are at greater risk, partly because of their longer life expectancy.[5 6] Furthermore, although the energy imparted is smaller in smaller patients, the corresponding organ masses are even smaller. This causes a marked increase in organ- and therefore patient-effective dose,[7 8] especially in younger children. A 1 year old infant is 10–15 times more likely to develop cancer than an adult for the same radiation dose. In effect, children's organs are more radiation sensitive and their longer life span allows the deleterious effects of radiation exposure to become manifest.[9]

The Late Effects Study Group followed a cohort of 1380 children with Hodgkin's disease to determine the incidence of second neoplasms and the risk factors associated with them.[10] Breast cancer was the most common solid tumour with an estimated actuarial incidence in women that approached 35% by 40 years of age. Older age (10–16 vs <10 years) at the time of radiation treatment (relative risk, 1.9) and a higher dose (2000–4000 vs <2000 cGy) of radiation (relative risk, 5.9) were associated with significantly increased risk of breast cancer. Children under the age of 18 at the time of the Chernobyl accident showed a four-fold increase in thyroid cancers diagnosed during the years 1990–1998.[11]

The effective doses for common radiological examinations are given in table 2.

ORGANISATION OF RADIATION PROTECTION IN THE UK

The International Commission on Radiological Protection (ICRP) has recommended systems of radiation protection, including dose limits, since 1928. Recommended dose limits have frequently been reduced since. In 1991 the dose limit to a member of the public from occupational use of ionising radiation was lowered to 1 mSv per year. This limit does not apply to the dose imparted to a patient by a medical exposure given to them as part of their own medical diagnosis or treatment. Protection of the patient is covered by the Medical

See end of article for authors' affiliations

Correspondence to: Waseem Mazrani, Radiology Department, Great Ormond Street Hospital for Children, London WC1N 3JH, UK; wmazrani@hotmail.com

Accepted 2 May 2007

Abbreviations: CNR, contrast-to-noise ratio; CR, computed radiography; CT, computed tomography; DAP, dose area product; DMSA, dimercaptosuccinic acid; DR, direct radiography; IRMER, Ionising Radiation (Medical Exposure) Regulations 2000; IRR99, Ionising Radiations Regulations 1999; LNT, linear, no threshold; MIBG, metaiodobenzylguanidine; MSCT, multi-slice CT; PET, positron emission tomography; SSCT, single-slice CT

Exposures Directive (European Council Directive 97/43/Euratom) which is implemented in the UK by the Ionising Radiation (Medical Exposure) Regulations 2000 (IRMER).[12] These regulations put the onus on those delivering the medical exposure to justify and optimise the use of ionising radiation for each exposure. An individual may fulfil more than one role. The limits of each role are set at a local level by the employer (usually the NHS Trust). Responsibilities are defined for the employer (to establish a framework for the protection of the patient), the referrer (who requests an exposure), a practitioner (who justifies the requested exposure by ensuring the benefits of the exposure outweigh the risks) and the operator (who performs the exposure in such a way as to ensure the desired outcome is achieved for the smallest possible radiation dose to the patient). Audit as part of clinical governance is used to monitor and optimise radiation dose with the ''as low as reasonably achievable'' (ALARA) principle in mind.

The Ionising Radiations Regulations 1999 (IRR99)[13] detail how the employer must establish, within their own organisation, a system of radiation protection governing the occupational use of ionising radiation. This system includes the designation of controlled and supervised areas, the provision of written local rules for persons working with radiation, the provision of monitoring and personal protective equipment, and engineering and procedural controls to restrict exposure as far as reasonably practicable. In doing so, the employer must appoint a qualified radiation protection adviser to advise on compliance with the regulations, and a radiation protection supervisor to supervise work in accordance with the local rules. IRR99 also details dose limits.

RADIOGRAPHY

Radiography is undoubtedly the most common imaging modality in paediatric radiology. Plain radiographs of dentition, limbs and the chest account for approximately 70% of all *x* rays in terms of frequency but contribute less than 2% to the overall population radiation dose.[14] Radiography may be traditional using analogue film-screen systems, or in digital format using computed radiography (CR) with a latent image or direct radiography (DR) without a latent image.

CR and DR have advantages over film-screen radiography. Images can be distributed electronically to an unlimited number of locations for viewing and storage and the presentation of the image can be modified. The latitude far exceeds that of film-screen radiography[15] and allows images to be obtained with larger variations in exposure. Consequently over-exposure will not necessarily result in poor image quality. This does, however, facilitate a potential for increased dose with no diagnostic penalty. The main downside of digital radiography is that spatial resolution of CR is worse compared with film-screen systems but, as with CT, superior contrast resolution helps to compensate for this. Of note, the reduced spatial resolution of the newer CR systems is not noticeable in everyday practice.

Various techniques are used to minimise paediatric dose in radiography. These may be technical, for example beam filtration, selection of appropriate beam kilovoltage and milliamperage, faster film-screen systems and accurate gonadal and breast shielding. Incidentally, at many institutions including our own, although gonadal shielding is not used on a first abdomen or pelvis radiograph, it is used routinely thereafter. Alternatively, techniques may be procedural, for example specialised radiographer training and standard type and number of projections for specific indications. Parents and carers are usually over 6 feet away from the *x* ray beam when children are being *x* rayed, and are often behind a lead shield and thus receive no excess irradiation in this setting. When a parent or carer assists in holding a child for an *x* ray, they (and particularly their radiation-sensitive organs such as the thyroid, breast and gonads) are far enough away from the primary beam that they receive no significant radiation dose.

Portable examinations should be mentioned here. These are performed on often the sickest patients, who tend to have repeated examinations. Additionally, in the paediatric setting a significant proportion will be low birth weight neonatal intensive care patients, where an unfortunate temptation to perform a ''babygram'' (a single exposure of the chest and abdomen, and often the whole child!) is at its peak. For an anteroposterior view of the chest, limitation of the field to exclude the gonads causes the gonad dose to be up to 100 times lower.[15] Including the chest and abdomen on the same radiograph inevitably results in overexposure of the chest. Considering that these babies sometimes have dozens of examinations, there is no place for ''babygrams''.

FLUOROSCOPY

IRMER stipulates that the employer must set local diagnostic reference levels (DRLs) for each standard examination. The dose area product (DAP, commonly measured in $cGy.cm^2$), the chosen indicator of dose in fluoroscopic examinations, should be ''as low as reasonably achievable'' whilst providing diagnostic images.[12]

Table 1 Glossary of technical terms

Term	Explanation
Absorbed dose	Energy absorbed from an ionising radiation per unit mass. Unit = Gray (Gy)
Collimation	This refers to limiting the *x* rays to a certain area in space. For instance, in CT this often refers to the slice thickness.
CNR	Contrast-to-noise ratio. The higher the CNR, the better the image quality and vice versa. Unfortunately higher CNR often involves imparting a higher dose to the patient.
CTDI	CT dose index. Determined on phantoms, usually 16 cm and 32 cm acrylic phantoms. Does not represent the dose to the individual patient, but is an indicator of the dose per CT slice.
Deterministic effects	These depend on cell killing and have a threshold dose for their induction.
Effective dose	Equivalent dose received by each individual organ or tissue multiplied by the appropriate tissue weighting factor and summing for all tissues involved. Unit = Sievert (Sv)
Equivalent dose	A measure of absorbed dose that accounts for the increased biological effect of high linear energy radiation. The absorbed dose is multiplied by the radiation weighting factor to produce the equivalent dose. This weighting is 1 for *x* rays, gamma rays and electrons, 5–20 for neutrons (depending on energy), 5 for protons and 20 for alpha particles, fission fragments and heavy nuclei. Unit = Sievert (Sv)
Gantry rotation time	The time taken for the CT *x* ray source to make a 360° revolution around the patient.
Grid	A grid is used for taking plain radiographs or fluoroscopy images in larger patients. A grid usually contains strips of lead and is placed between the patient and the film. The lead absorbs most of the scattered *x* rays which hit the grid obliquely while allowing the primary beam through. This increases resolution but unfortunately also increases dose.
Scan pitch	The ratio of the table movement to the *x* ray beam width for one tube rotation.
Stochastic effects	These depend on cell transformation, are random and have no threshold dose. Severity is unrelated to dose and may be heritable.

Table 2 Comparison of effective doses

Examination	Typical effective dose (mSv)	Equivalent number of chest *x* rays	Equivalent length of background exposure
x Ray			
Limbs and joints (except hip)	<0.01	<0.5	<1.5 days
Chest (single PA)	0.02	1	3 days
Skull	0.07	3.5	11 days
Lumbar spine	1.3	65	7 months
Hip	0.3	15	7 weeks
Pelvis	0.7	35	4 months
Abdomen	1.0	50	6 months
IVU	2.5	125	14 months
Barium meal	3	150	16 months
CT head	2.3	115	1 year
CT chest	8	400	3.6 years
CT abdomen or pelvis	10	500	4.5 years
Radionuclide studies			
Kidney (^{99m}Tc)	1	50	6 months
Thyroid (^{99m}Tc)	1	50	6 months
Bone (^{99m}Tc)	4	200	1.8 years
PET head (F-18 FDG)	5	250	2.3 years

Effective doses for common radiological examinations expressed in terms of the equivalent number of chest radiographs and length of exposure to background radiation that would give the same dose.[1] IVU, intravenous urogram; PA, posterior-anterior.

Dose depends on the intrinsic properties of the child, for example, age, sex, body mass, body thickness and other factors including the cooperation of the child, the type of equipment and the operator.[16] Better equipment allows the technical parameters to be optimised. Key components of minimising dose include using low fluoroscopy frame rates (three frames per second compared with the standard 15 frames per second), last image hold, using lower resolution so-called frame-grabbed images and reserving full exposures for fine detail, collimation using a light beam diaphragm or electronic means rather than *x* ray fluoroscopy for patient positioning, avoiding use of a grid before 8 years of age unless a child is large for age, and appropriate beam filtration.

Pregnant mothers are generally advised against staying in a fluoroscopy room during a radiological investigation because of a theoretical radiation risk to the foetus. Parents and carers assisting, for example, with a micturating cystourethrogram, are of course required to wear a lead apron but as they are away from the primary beam, the radiation dose received by carers is negligible in this setting.

NUCLEAR MEDICINE

In the United Kingdom, medical radioactive products must be prescribed by a doctor or dentist in possession of an Administration of Radioactive Substance Advisory Committee (ARSAC) licence. The most commonly used isotope is ^{99m}technetium (^{99m}Tc).

Technetium

^{99m}Tc is used in 90% of radionuclide imaging as it has many desirable properties.[17] It has a short half life of 6 h and pure gamma emission of 140 keV, helping to minimise patient dose. It is easily collimated and absorbed in a fairly thin crystal, thus giving good spatial resolution. Technetium is readily available on hospital sites and can be easily labelled to a wide variety of useful compounds, for example dimercaptosuccinic acid (DMSA), mercaptoacetyltriglycine (MAG3) and diethylene triamine pentacetic acid (DTPA) for renal imaging, diphosphonates for bone imaging, and sestamibi for cardiac perfusion imaging.

Metaiodobenzylguanidine (MIBG)

MIBG is used in the treatment of neuroblastoma for diagnosis, staging, follow-up and therapy. MIBG specificity is near 100% and sensitivity is 90–95% for this tumour.[18 19] MIBG scanning is also useful in screening for phaeochromocytoma.

MIBG is a false transmitter and structurally similar to norepinephrine. MIBG may be iodinated with ^{123}I or ^{131}I. Preparation of the patient includes thyroid blockade with oral iodine to reduce the dose from free radioiodide that forms in vivo.[20–22]

^{123}I, a pure gamma emitter, is near ideal with a half life of 13 h and a photon energy of 159 keV. By comparison ^{131}I, a gamma emitter which also emits beta particles, has a half life of 8 days and a photon energy of 364 keV, giving a whole body radiation dose 20 times higher compared to ^{123}I.[23] ^{123}I-MIBG is used for diagnostic imaging whilst the higher dose ^{131}I-MIBG may be used as a therapeutic agent alone[24] or in combination with chemotherapy in known MIBG-avid metastatic tumours.[25–28]

Positron emission tomography (PET)

PET provides metabolic information dependent on the tracer used. This can complement largely morphological information derived from other imaging. FDG-PET in oncology is based on cancer cells being more dependent on anaerobic glycolysis than normal cells.[29 30] Spatial resolution is relatively poor (4–5 mm) but co-registration with PET-CT helps overcome this and results in higher diagnostic accuracy with fewer equivocal findings.[31] This has largely replaced conventional PET. Although the addition of a CT scanner to PET-CT facilitates patient transmission correction, PET-CT delivers a higher radiation burden than PET alone.

Many questions remain to be answered regarding the use of PET and PET-CT in various conditions such as epilepsy, cardiac anomalies and malignancies. However, the current major limitation is high sensitivity for abnormal tracer uptake but poor specificity for malignancy. For example, an intercurrent respiratory tract infection may make tracer-avid head and neck nodes indistinguishable from lymphomatous nodes.

COMPUTED TOMOGRAPHY (CT)

CT accounts for approximately 9% of all radiological examinations but is responsible for 47% of medical radiation dose.[32–35] Approximately 11% of CT examinations performed are in the paediatric population. The continuing evolution of new CT technology with faster scanning times and high resolution means that the number of CT examinations in children, already in the millions worldwide per year, will likely continue to increase. For example, cardiac CT examinations, previously seldom indicated in paediatric patients, are now widely carried out.

CT image contrast is directly related to the mean photon energy. The most significant determinant of the latter is *x* ray tube voltage. Kilovoltage has an exponential relationship with dose,[36] so any reduction has the potential to greatly reduce dose. Patient size is also a modest determinant of image contrast, as increasing patient size means increasing mean photon energy due to preferential loss of low energy photons (beam hardening). Patient size is, however, a major determinant of CT image noise, with increasing size leading to increasing noise. Nonetheless, the most important determinant of image noise is the number of *x* ray photons used, that is tube current. In comparison to normal-sized adults, image contrast-to-noise ratio (CNR) for neonates is a factor of four higher if the same kV and mAs are used. To maintain the same CNR in infants as in adults, both mAs and kV should be modified.

Unfortunately higher dose adult techniques have often been applied to children,[37] which can lead to excessive and

unnecessary radiation dose. Indeed, 2 years after an article in the *American Journal of Roentgenology*, which pointed out the high radiation burden inherent in all CT examinations, had provoked much controversy, only 43% of imaging departments indicated that they had made any adjustment in technique for paediatric patients.[33] In one survey of members of the Society of Pediatric Radiology, only 33% of respondents indicated that they performed helical CT of the chest in children 4 years old and younger with a tube current of less than 100 mAs.[38]

Many CT examinations in the paediatric population may not actually be necessary. It has been estimated that up to 30–40% of paediatric CT studies performed in the USA are not indicated.[39] These must be eliminated. If CT examination is justified, then techniques specific to and appropriate for the child's age, size (ranging from premature neonates to oversized adult proportions), region to be imaged and the particular indication for the examination should be used. Sedation may be required to ensure acquisition of images of adequate quality at the first attempt.

Multiphase examinations should only rarely be necessary. It is tempting to perform scans through the liver, for example, at the arterial, venous equilibrium and portal venous phases but these additional CT runs seldom add useful extra information in paediatric practice (the importance of ultrasound scanning should not be overlooked). Performing two phases using the same parameters doubles the radiation dose. Consequently, if an extra phase of examination is performed, parameters should be adjusted to reduce dose. For example, a pre-contrast scan to detect calcification in a lesion may be done adequately with lower dose, noisier images.[40] It must be stressed here that non-ionising techniques such as ultrasound and MRI should be used before CT whenever possible in the paediatric setting. MR scanning may require anaesthesia or sedation, but this may be preferable to repeated CT (for example in a child with a malignancy).

Lower dose, noisier CT images may also be acceptable and diagnostic where there is intrinsic high contrast, for example, in paediatric chest and musculoskeletal CT, and with CT angiography.[40–45] Factors that will reduce dose include lowering kilovoltage, lowering tube current, decreasing gantry rotation time and increasing pitch.

Gantry rotation time (s) affects radiation dose. This is a linear relationship.[46] Decreasing the gantry rotation cycle time from 1.0 to 0.5 s decreases the radiation dose by 50%. As fast a gantry rotation time as possible should be used. This decreases movement artefact and is important because of a child's limited capacity for co-operation.

In a single-slice CT (SSCT), pitch is the ratio of table movement per gantry rotation (mm) to collimation (mm): the higher the pitch, the lower the radiation dose. However, higher pitch results in more scan artefact and lower resolution. In spiral CT, if pitch is greater than unity, then a reduction in dose is achieved in comparison with contiguous axial scans. SSCT pitches of 1.5 have been shown to reduce radiation dose by approximately 33% compared with a pitch of 1, with no loss in diagnostic accuracy.[47] In multi-slice CT (MSCT), pitch is independent of gantry rotation time.[40] For MSCT, collimation equals the total width of all the detector channels. Dose can be reduced by using thicker detector configurations, resulting in fewer rotations to cover the same distance.

There are many differing views on how best to reduce dose in CT while not losing diagnostic accuracy. One dose reduction regimen is based on a colour-coded chart of patient weight.[48] Others have championed the use of image-noise measurements to adjust chest, abdomen and pelvis CT techniques, claiming a decrease in measured entrance dose of 60–90%.[49] Others believe body diameter is a better parameter as patients with different body habitus may have the same weight.[50] Until recently, our institution used the child's weight to set the mAs for a chest CT,[51] with no more than 20 mAs per slice for children weighing less than 15 kg and no more than 55 mAs for those weighing up to 44 kg.

Traditionally, a single tube current was used to scan an entire region of varying attenuations. The latest CT scanners have automatic exposure control, where the *x* ray tube current is automatically adjusted, based on the attenuation of the section being scanned, providing for a decreased overall dose. Dose reduction has at last become a priority for many manufacturers.[52–55]

CONCLUSIONS

Is imaging required at all? This should be the first question for clinicians and radiologists alike in any given clinical scenario. If there is a clear indication for imaging, then it should be recognised that unnecessary ionising radiation examinations must be avoided. For instance, ultrasound of an abdominal mass or soft tissue lump should always be performed before considering CT. Radiation dose, particularly in a paediatric setting, must be as low as possible.

Imaging algorithms for the most commonly encountered paediatric disorders should be developed in a multidisciplinary setting, especially when new technology is being introduced. In individual clinical scenarios, particularly if complex, clinicians must ask the advice of radiologists. Comprehensive clinical information and optimal patient preparation will help to establish the best diagnostic test at a minimum radiation dose. Clearly the appropriate modality must be chosen and those that do not use ionising radiation should be chosen preferentially whenever possible.

Optimising the relationship between diagnostic accuracy and patient dose must be uppermost in the thoughts of all members of the team. For example, manufacturers are providing dose-efficient hardware and software for CT scanners. Employers must provide adequate education and training for their staff to make best use of these facilities.

Currently, it is not easy to directly measure effective dose in diagnostic radiology. However, measures such as CTDI in CT and DAP in fluoroscopy are readily available, provide a gauge of patient dose and may be increasingly important as documentation of radiation dose estimates becomes routine.

The principal concern in imaging, especially in children, concerns stochastic effects. We are aware of at least one ongoing, large epidemiological study of the cancer risk attributable to CT examinations in childhood (M Pearce, personal communication), which is funded by the National Cancer Institute (USA) and Department of Health (UK). It must be hoped that studies of this kind will aid future discussions on the subject of ionising radiation dose, risks and benefits.

The aim of diagnostic imaging should be adequate image quality rather than optimal image quality, particularly when the latter involves increased patient dose with no discernable increased diagnostic benefit. The long-term detrimental effects of diagnostic radiography, particularly in young girls undergoing CT examinations, need to be studied.

Authors' affiliations
W Mazrani, K McHugh, P J Marsden, Radiology Department, Great Ormond Street Hospital for Children, London, UK

Competing interests: None.

REFERENCES

1 **Grainger RG**, Allison D, Adam A, *et al. Grainger and Allison's diagnostic radiology*, 4th edn. London: Churchill Livingstone, 2001.
2 **National Radiological Protection Board**. *Living with radiation*, 5th edn. Didcot, UK: NRPB, 1998.
3 **International Commission on Radiological Protection**. *1990 recommendations of the International Commission on Radiological Protection*. Oxford, UK: Pergamon, 1991:60.
4 **Pierce DA**, Preston DL. Radiation-related cancer risks at low doses among atomic bomb survivors. *Radiat Res* 2000;**154**:178–86.
5 **BEIR V (Committee on the Biological Effects of Ionizing Radiation)**. *Health effects of exposure to low levels of ionizing radiation*. Washington, DC: National Academies Press, 1990.
6 **Slovis TL**. The ALARA concept in pediatric CT: myth or reality? *Radiology* 2002;**223**(1):5–6.
7 **Ware DE**, Huda W, Mergo PJ, *et al*. Radiation effective doses to patients undergoing abdominal CT examinations. *Radiology* 1999;**210**(3):645–50.
8 **Huda W**, Atherton JV, Ware DE, *et al*. An approach for the estimation of effective radiation dose at CT in pediatric patients. *Radiology* 1997;**203**(2):417–22.
9 **Hall EJ**. Lessons we have learned from our children: cancer risks from diagnostic radiology. *Pediatr Radiol* 2002;**32**(10):700–6.
10 **Bhatia S**, Robison LL, Oberlin O, *et al*. Breast cancer and other second neoplasms after childhood Hodgkin's disease. *N Engl J Med* 1996;**334**(12):745–51.
11 **UNSCEAR (United Nations Scientific Committee on the Effects of Atomic Radiation)**. *2000 Report to the General Assembly, with scientific annexes. Exposures and effects of the Chernobyl accident*, Annex J. New York: United Nations, 2000:453–566.
12 **Department of Health**. *The ionising radiation (medical exposure) regulations, 2000*. London: DoH, 2000.
13 **Health and Safety Executive**. *Ionising radiations regulations, health and safety 1999*, SI 3232/1999. London: HMSO, 1999.
14 **Hart D**, Wall BF. *Radiation exposure of the UK population from medical and dental x-ray examinations*, NRPB Report W4. Didcot, UK: National Radiological Protection Board, 2002.
15 **Willis CE**. Computed radiography: a higher dose? *Pediatr Radiol* 2002;**32**(10):745–50.
16 **Hiorns MP**, Saini A, Marsden PJ. A review of current local dose-area product levels for paediatric fluoroscopy in a tertiary referral centre compared with national standards. Why are they so different? *Br J Radiol* 2006;**79**:326–30.
17 **Farr RF**, Allisy-Roberts PJ. *Physics for medical imaging*. London: Saunders, 1998.
18 **Gelfand MJ**. Meta-iodobenzylguanidine in children. *Semin Nucl Med* 1993;**23**(2):231–42.
19 **Parisi MT**, Greene MK, Dykes TM, *et al*. Efficacy of metaiodobenzylguanidine as a scintigraphic agent for the detection of neuroblastoma. *Invest Radiol* 1992;**27**(10):768–73.
20 **Nakajo M**, Shapiro B, Copp J, *et al*. The normal and abnormal distribution of the adrenomedullary imaging agent m-[I-131]iodobenzylguanidine (I-131 MIBG) in man: evaluation by scintigraphy. *J Nucl Med* 1983;**24**(8):672–82.
21 **van Santen HM**, de Kraker J, van Eck BL, *et al*. Improved radiation protection of the thyroid gland with thyroxine, methimazole, and potassium iodide during diagnostic and therapeutic use of radiolabeled metaiodobenzylguanidine in children with neuroblastoma. *Cancer* 2003;**98**(2):389–96.
22 **Olivier P**, Colarinha P, Fettich J, *et al*. Guidelines for radioiodinated MIBG scintigraphy in children. *Eur J Nucl Med Mol Imaging* 2003;**30**(5):B45–50.
23 **Shulkin BL**, Shapiro B. Current concepts on the diagnostic use of MIBG in children. *J Nucl Med* 1998;**39**(4):679–88.
24 **Hoefnagel CA**, Voute PA, de Kraker J, *et al*. Radionuclide diagnosis and therapy of neural crest tumors using iodine-131 metaiodobenzylguanidine. *J Nucl Med* 1987;**28**(3):308–14.
25 **Corbett R**, Pinkerton R, Tait D, *et al*. [131I]metaiodobenzylguanidine and high-dose chemotherapy with bone marrow rescue in advanced neuroblastoma. *J Nucl Biol Med* 1991;**35**(4):228–31.
26 **Gaze MN**, Wheldon TE, O'Donoghue JA, *et al*. Multi-modality megatherapy with [131I]meta-iodobenzylguanidine, high dose melphalan and total body irradiation with bone marrow rescue: feasibility study of a new strategy for advanced neuroblastoma. *Eur J Cancer* 1995;**31A**(2):252–6.
27 **Klingebiel T**, Bader P, Bares R, *et al*. Treatment of neuroblastoma stage 4 with 131I-meta-iodo-benzylguanidine, high-dose chemotherapy and immunotherapy. A pilot study. *Eur J Cancer* 1998;**34**(9):1398–402.
28 **Yanik GA**, Levine JE, Matthay KK, *et al*. Pilot study of iodine-131-metaiodobenzylguanidine in combination with myeloablative chemotherapy and autologous stem-cell support for the treatment of neuroblastoma. *J Clin Oncol* 2002;**20**(8):2142–9.
29 **Warburg O**. On respiratory impairment in cancer cells. *Science* 1956;**124**(3215):269–70.
30 **Som P**, Atkins HL, Bandoypadhyay D, *et al*. A fluorinated glucose analog, 2-fluoro-2-deoxy-D-glucose (F-18): nontoxic tracer for rapid tumor detection. *J Nucl Med* 1980;**21**(7):670–5.
31 **Tsukamoto E**, Ochi S. PET/CT today: system and its impact on cancer diagnosis. *Ann Nucl Med* 2006;**20**(4):255–67.
32 **Shrimpton PC**, Edyvean S. CT scanner dosimetry. *Br J Radiol* 1998;**71**(841):1–3.
33 **Linton OW**, Mettler FA Jr. National conference on dose reduction in CT, with an emphasis on pediatric patients. *AJR Am J Roentgenol* 2003;**181**(2):321–9.
34 **Mettler FA Jr**, Wiest PW, Locken JA, *et al*. CT scanning: patterns of use and dose. *J Radiol Prot* 2000;**20**(4):353–9.
35 **Hart D**, Wall BF. UK population dose from medical X-ray examinations. *Eur J Radiol* 2004;**50**(3):285–91.
36 **Frush DP**, Donnelly LF, Rosen NS. Computed tomography and radiation risks: what pediatric health care providers should know. *Pediatrics* 2003;**112**(4):951–7.
37 **Paterson A**, Frush DP, Donnelly LF. Helical CT of the body: are settings adjusted for pediatric patients? *AJR Am J Roentgenol* 2001;**176**(2):297–301.
38 **Hollingsworth C**, Frush DP, Cross M, *et al*. Helical CT of the body: a survey of techniques used for pediatric patients. *AJR Am J Roentgenol* 2003;**180**(2):401–6.
39 Slovis TL, ed. ALARA Conference Proceedings: the ALARA concept in pediatric CT - intelligent dose reduction, *Pediatr Radiol* 2002;**32**(4):217–317.
40 **Frush DP**. Pediatric CT: practical approach to diminish the radiation dose. *Pediatr Radiol* 2002;**32**(10):714–17.
41 **Mayo JR**, Hartman TE, Lee KS, *et al*. CT of the chest: minimal tube current required for good image quality with the least radiation dose. *AJR Am J Roentgenol* 1995;**164**(3):603–7.
42 **Zhu X**, Yu J, Huang Z. Low-dose chest CT: optimizing radiation protection for patients. *AJR Am J Roentgenol* 2004;**183**(3):809–16.
43 **Ravenel JG**, Scalzetti EM, Huda W, *et al*. Radiation exposure and image quality in chest CT examinations. *AJR Am J Roentgenol* 2001;**177**:279–84.
44 **Fayad LM**, Johnson P, Fishman EK. Multidetector CT of musculoskeletal disease in the pediatric patient: principles, techniques, and clinical applications. *Radiographics* 2005;**25**:603–18.
45 **Siegel MJ**. Pediatric CT angiography. *Eur Radiol* 2005;**15**(Suppl 4):D32–6.
46 **Smergel E**, Benson D. Radiation dose on pediatric CT: losing track of time. *AJR Am J Roentgenol* 2002;**178**(2):507–8.
47 **Vade A**, Demos TC, Olson MC, *et al*. Evaluation of image quality using 1: 1 pitch and 1. 5: 1 pitch helical CT in children, a comparative study. *Pediatr Radiol* 1996;**26**(12):891–3.
48 **Frush DP**, Soden B, Frush KS, *et al*. Improved pediatric multidetector body CT using a size-based color-coded format. *AJR Am J Roentgenol* 2002;**178**(3):721–6.
49 **Cody DD**, Moxley DM, Krugh KT, *et al*. Strategies for formulating appropriate MDCT techniques when imaging the chest, abdomen, and pelvis in pediatric patients. *AJR Am J Roentgenol* 2004;**182**:849–59.
50 **Haaga JR**. Radiation dose management: weighing risk versus benefit. *AJR Am J Roentgenol* 2001;**177**(2):289–91.
51 **McHugh K**. CT dose reduction in pediatric patients. *AJR Am J Roentgenol* 2005;**184**(5):1706–7.
52 **Fox SH**, Toth T. Dose reduction on GE CT scanners. *Pediatr Radiol* 2002;**32**(10):718–23.
53 **Morgan HT**. Dose reduction for CT pediatric imaging. *Pediatr Radiol* 2002;**32**(10):724–8.
54 **Suess C**, Chen X. Dose optimization in pediatric CT: current technology and future innovations. *Pediatr Radiol* 2002;**32**(10):729–34.
55 **Westerman BR**. Radiation dose from Toshiba CT scanners. *Pediatr Radiol* 2002;**32**(10):735–7.