Dose Optimization and Reduction in CT of Children

15

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CONTENTS

Radiation risks based on biology and physics have been covered in previous chapters and are, of course, also valid for children. In the same way, clinical approaches to dose optimization and reduction are similar in paediatric and adult CT examinations (Huda et al. 2000). This chapter will not repeat what has been said but concentrate on the fact that children are not just adults with smaller dimensions, thus it will rather point out what is different in children.

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15.1 Why Dose Optimization and Reduction in CT is Even More Important in Children than in Adults

Several independent arguments clearly justify an even more careful use of the "as low as reasonably achievable" (ALARA) principle in children than in adults (Frush et al. 2003; Vock 2002) (Table 15.1):

- Children are indeed – depending on their stage of growth – *smaller* than adults, and this means that the physical laws of radiation interaction and absorption have to be respected during protocol definition (Boone et al. 2003; Chapple et al. 2002; Frush 2002; Huda 2002; Huda and Gkanatsios 1997). Usually, a decreased number of photons is required, which translates into a lower tube output (mAs). Often the use of a lower X-ray energy (kV) is appropriate as well in children. These facts – though known for over decades for radiography – were not realized for computed tomography (CT) by many radiologists until the early years of the new millennium (Paterson et al. 2001).
- At the same physical exposure to ionizing radiation, the *biological effects* are *more severe* in children than adults (Brenner 2002; Brenner et al. 2001, 2003; Frush et al. 2003; Pierce and Preston 2000); the risk of lethal cancer is multiplied by a factor of 2.5 on average, as compared to adult people, starting at around 10 in neonates and approaching adult values during adolescence. This is mostly explained by the fact that proliferating tissues are more vulnerable to the effects of radiation and that proliferation is much more active during the growth period than later in life. Furthermore the distribution of tissues is different in childhood: e.g. red bone marrow will hardly be irradiated during a CT extremity exam in adults whereas it will partly be included in the volume of primary radiation exposure in a child.

Table 15.1. Why children need specific CT planning

Difference	Cause, consequence
1. Smaller dimensions	Adapt protocol according to physics
2. Higher biologic sensitivity	Growth, cell proliferation, tissue distribution
3. Long life expectancy	Increased risk of tumor manifestation
4. Less fatty tissue	Adapt protocol to maintain contrast
5. Cooperation may not be possible	Prepare patient, immobilize, scan fast
6. Alternative imaging test equivalent	Ultrasound, MRI more often equivalent
7. Different pathology in children	Requires different justification/approach

- Children have a *longer life expectancy* than the average adult population studied by CT. Their natural life time left at the moment of CT scanning is in the range of 70 years whereas it is more often 10–20 years than 30–40 years in the adult CT population. Of course, since it is likely that the risk of radiation-induced carcinogenesis persists during the entire life span and since the delay of cancer manifestation is more often decades than years, more children than adults will be alive at the end of the latency period of radiation-induced cancers, and a significant percentage among them will die from cancer.
- Children usually have *less fatty tissue* between visceral organs than adults. To keep the contrast needed to differentiate structures with only tiny fatty layers in between, the signal-to-noise (*S*/*N*) ratio, and thus the dose, has to be increased, or the contrast has to be improved by other modifications of the protocol, such as by using a lower X-ray energy (kV).
- *Cooperation* is not as easy for children as it is for adults. This means that the combined contributions of trained personnel, patient preparation, the atmosphere in the examination room and sometimes the presence of a parent are all needed to reach an optimal result using minimal radiation exposure.
- *Alternatives* to CT exist in children – in contrast to multiple applications in adults. Children are excellent candidates for *ultrasound* imaging, and – unlike in adults – many more details in more regions of the body can be shown. Cerebral ultrasound in the neonate is just one prominent example. Similarly, *magnetic resonance imaging* (*MRI*), another alternative to CT without ionizing radiation, has an excellent accuracy in children; most contraindications to MRI, such as cardiac pacemakers, neurostimulators, ferromagnetic foreign bodies, or claustrophobia, are rarely a problem in children.
- *Pathology is different* in children than in adults. While congenital and inflammatory disorders are more frequently seen, degenerative and neoplastic diseases are clearly less abundant during the growth period. A different spectrum of pathology means a different diagnostic approach. Above all, justification follows the specific pathology and does not just ask for the best technical method for one organ but rather for weighing the advantages and risks of all methods in the specific situation.

15.2 Impact of New CT Scanners on Paediatric Patients

As medical aspects and the biologic impact of CT scanning are different in children than in adults, the impact of the recent technical development of CT scanners is special in children and requires some consideration (Table 15.2). Many new options come up, but these advantages have to be balanced with the disadvantages that are often tightly combined. In a phase of fast development there are of course major differences between the scanners of different manufacturers. Because these will level out, mostly within a few years, we will concentrate on the issues that all multi-row detector scanners have in common.

Table 15.2. Impact of modern CT scanners on paediatric CT

Technical feature of modern CT	Consequence
1. Faster scanning	Less cooperation/immobilization needed, new applications (e.g. vascular, multi-phasic), larger volume covered per time
2. Better *z*-axis resolution	Isotropic geometric resolution, noise
3. Slice thickness	Correct slice profile, more noise on thin slices (or increased radiation exposure)
4. Dose shaping (bow tie) filters	Useful for object with small dimensions
5. Dose modulation	Constant *S*/*N*, dose reduction (if used appropriately)
6. Geometric detector efficiency	*z*-axis overbeaming (collimation), non-detector area (element spacing)
7. Additional rotation in spiral mode needed for interpolation	Additional dose outside planned volume

- *Faster scanning*: this is obviously the single most important factor for the growing number of applications of CT in paediatrics (Mettler et al. 2000; Nickoloff 2002; Nickoloff and Alderson 2001). Children no longer need to stay immobile for 10–15 min, and often CT scanning is possible without sedation or with sedation instead of intubation anaesthesia. Motion artefacts have mostly disappeared, and the body volume studied during one session is no longer limited by the maximal period of cooperation of a child. Vascular applications of CT in children have only become available with modern scanners, thanks to the fact that the first or second pass of contrast agents can be used to get a high intravascular contrast before diffusion to the interstitial space occurs. Similarly, multiphasic examinations essentially have only been introduced with the arrival of the modern generation of CT scanners. New medical applications indeed are the most important reason for an important rise in the number of CT examinations performed in children during the last 10 years.
- *Better z-axis resolution*: the smaller dimensions of children basically require a high geometric resolution, with ideally isotropic voxels. The *z*-axis size of a voxel, a major problem with single detector rows, can be reduced to even submillimetric dimensions on scanners with multiple detector rows, without compromising the volume coverage of the scan. This is a major advantage, particularly for avoiding partial volume effects and secondarily for multiplanar 2D reformations and for 3D analysis of data.
- *Slice thickness*: thinner collimation in multi-row detector CT scanners produces raw data of an intrinsically high geometric resolution. However, the smaller submillimetric voxel volume necessarily causes a major signal drop and, thus, a drop of the *S*/*N* unless the X-ray flux is increased proportionally. This phenomenon has had an impact on the clinical application of four-detector-row scanners, where radiation exposure has risen in relation to single-row scanners. To handle this physical fact, most experts now suggest scanning at a thin collimation and a low dose but then reconstructing thicker images of 3–6 mm with a much better *S*/*N* for diagnosis. Thus, thin noisy slices are just consulted in cases of partial volume problems, and they are used for post-processing. In conclusion, it is useful to have the submillimetric slices available but to rely mostly on thicker ones for routine work, even in children. Another problem with slice thickness and single-row scanners has occurred: using an elevated pitch (1.5–3), as needed for faster scanning and for dose reduction, has caused a major widening of the slice profile. With multi-row scanners – thanks to more data available for interpolation – the slice profile is close to the nominal value, and the pitch factor has lost most of its critical influence.
- *Dose shaping filters (bow tie filters)*: dose shaping filters are used to adapt the X-ray profile. Obviously, objects with a diameter much less than the diameter of the gantry do not require the same X-ray flux in the periphery of the field of view compared to thick objects. Specific filters are used by most manufacturers to adapt the beam profile to the smaller dimension of an adult head, an extremity or a child, and they help to control radiation exposure.

- *Dose modulation*: the introduction of dose modulation in CT corresponds practically to automatic exposure control as used in fluoroscopy systems to keep the *S*/*N* at the detector constant during an examination. Body areas with smaller diameters and moderate bony components do not require the same X-ray flux as thick areas with a lot of bony structures. Dose modulation in the *xy*-plane and the *z*-axis is therefore a major step forward that should be used generally. However, let us keep in mind that it is not perfect at all. Depending on the modulation rules used by the manufacturer, modulation may even increase exposure beyond the nominal value, e.g. when the scan starts at a level with a thin body diameter, or when local organ shielding is used for the thyroid or the breast gland. The degree of adaptation of exposure to the local physical absorption (in order to maintain a constant *S*/*N* at the detector) also depends on the relation between the length of the detector and the length of the scan. When a scan covers only a small distance, as appropriate in scanning one anatomical region of a child, and when the detector – due to many rows (e.g. 64) – becomes long in the *z*-axis, the best modulation of tube output will fit the needs of the central detector elements whereas the elements above and below may receive too many or too few photons. In other words, the efficacy of dose modulation intrinsically decreases with an increasing number of detector rows. This is true, independently of the type of modulation, whether based on absorption measurements from localizer scans or interactively on the data on the previous rotation.
- Geometric detector efficiency: geometric efficiency of modern CT scanners is mostly determined by two factors, the z-axis geometric efficiency and the detector array geometric efficiency. To avoid penumbral effects in the outer portions of the detector array, collimation of the X-ray beam is usually set wider than the length of the detector array in multi-row scanners; this means a decreased z-axis geometric efficiency and, consecutively, an increase in exposure due to X-rays that will not hit the detector. The effect is most severe with four-row scanners and with narrow submillimetric slices; in this extreme condition, dose may be doubled (Chap. 4 by H.D Nagel) whereas the increase is rather in the range of 5%–20% with 8- to 64-row scanners (impact scan). As for dose modulation, this phenomenon is physically the same in children and in adults but again – due to the small dimension of a child's body – the effects beyond the planned and properly detected proportion of X-rays may easily extend to critical organs not to be studied in children, such as the thyroid in chest exams or the testes in abdominal exams.

  Detector array geometric efficiency is defined by the proportion of the overall detector area that contains active detector material. The proportional area of septa between active elements generally increases with the number of detector elements in the *xy*-plane and as well as with the number of rows in the *z*-axis. Again this effect is not unique in children but has to be considered in paediatric CT.
- *Additional rotations for interpolation in spiral mode*: projections outside the reconstructed *z*-axis range are needed in spiral (helical) mode at each end of the scan. Since spiral scanning has become the standard in most CT applications, this phenomenon must not be forgotten. The relative contribution to radiation exposure is more important the shorter the scan length. It also increases with multi-slice scanners since these usually have a larger total collimation (i.e. the sum of all detector elements in the *z*-axis). Again, in paediatric CT we have to be aware of radiation exposure beyond the planned scan range, e.g. with 64 rows of 0.6 mm detector length, half an additional rotation at pitch 1 will cover nearly 2 cm more both at the top and the bottom, whereas with a pitch of 2, nearly 4 cm of the body will be scanned outside the volume of interest. As for *z*-axis geometric efficiency, important organs outside our scanning volume might be exposed to direct instead of scattered radiation and receive a significant dose.

15.3 Justification

The "as low as reasonably achievable" (ALARA) principle may mean that an imaging study using ionizing radiation has to be cancelled when there is an equivalent test available that does not need radiation exposure: the global sum of its advantages has to be greater than the sum of its disadvantages in order to justify a specific test. Indeed, justification is the single most effective step in radiation protection. No other step discussed later will reduce

exposure by 100%, and even when a CT exam is replaced by another X-ray study, this usually means a major reduction of exposure since most other X-ray examinations cause a much smaller effective dose than CT studies (Shrimpton et al. 2005; Ware et al. 1999). However, justification is also the most difficult step since the risk of immediately not doing the examination cannot be directly compared with the long-time risk of inducing cancer (Vock 2005). What may be good for an elderly patient in internal medicine may not be an appropriate approach for a paediatric patient. Imaging studies not only involve ionizing radiation but also a number of other risks and chances, and they are often quite expensive. Depending on the specific medical infrastructure of a country, there is still a lack of high-tech equipment, and doing the study on the wrong patient may exclude another patient from getting the same CT examination that may be critical for his or her treatment or even the survival.

Slovis (2002) estimated around 40% of all paediatric CT examinations as not clearly indicated. All these reasons together underscore the importance of justification. Several countries have developed guidelines in using imaging procedures: in the US, the *appropriateness criteria* defined by a panel of experts (using a score of 1–9) have been introduced by the American College of Roentgenology (2006). For instance, appropriateness of CT of the brain in suspected physical child abuse will be low (2, mostly inappropriate) or very high (9, most appropriate), depending on the age, the results of physical examination and laboratory exams. The European Union (European Commission 2000b) has issued *referral criteria for imaging* that have been translated into many languages. In the referral criteria, paediatrics makes up an entire section that is further classified by anatomical areas and, within each area, by important clinical entities. Except for trauma, CT is rarely mentioned and the conditions for its use are further commented. It is obvious that major efforts are still needed to differentiate the diagnostic decision trees in specific clinical situations, including the age, the pathology, the body region as well as the urgency and the availability of alternative diagnostic tools.

Head trauma is also an example for clinical criteria helping to decide about the individual need for CT evaluation (Oman et al. 2006). Hardly ever is medical diagnostic imaging justified just for demonstrating morphology; as is true for any other diagnostic tests it is expected to detect disease, to differentiate between different pathologies, to stage disease or to provide information about the effects of treatment. However, all this information is not helpful unless it helps in the further management of the patient and is obtained with an appropriate "cost". Cost clearly includes both the financial cost of the examination and its medical risk. In paediatric CT, although there are risks with anaesthesia and intravenous contrast medium injection, the main two risks usually are the inaccuracy of the test (false-negative, false-positive findings) and the risk of radiation exposure, which is more important than in adult patients, even at the same nominal effective dose.

Before any imaging examination with x-rays is considered, alternatives must therefore be evaluated: ultrasound is the first-line imaging test in children since the slim body usually favours the access even to deep organs without any radiation exposure, combining morphological with real-time motional and even flow information. In experienced hands, it can provide a lot of essential information, thus avoiding CT. When ultrasound and radiography are unlikely to answer – or have not answered – the specific medical question, the choice is often between MRI and CT. In this situation severity of suspected disease, study duration, radiation exposure, side-effects of contrast agents and anaesthesia, volume of interest and the specific information required have to be considered in addition to the availability of the method. While there is no general answer, a disease concentrated in one organ or one limited region of the body, and situations requiring detailed information about soft tissues, the nervous system, the cardiovascular system or the bone marrow are often best approached by MRI. On the other hand, a large volume of the body, time and anaesthetic restrictions and emergency conditions, such as multiple trauma, as well as the need for information about cortical bone and calcification, or the combination with image-guided intervention all favour CT. Malignant disease with a poor prognosis will decrease the weight of radiation exposure; however, with an increasing chance of curative treatment – e.g. in malignant lymphoma – the added risk of many follow-up studies under and after treatment must be considered.

Follow-up CT scans are often performed too early, e.g. at a moment when the biology of the disease does not yet allow any treatment effects to be visible. Justification has to be as restrictive as for the first examination, and alternatives may be adequate for observing known manifestations of disease. Justifi-

cation as the first step of diagnostic imaging means a close cooperation between the referring doctor and the radiologist since it cannot be done by the clinician alone or by the radiologist alone. Both need education to adequately perform this important task; it is obvious that subspecialized paediatric radiologists will have a significant advantage of knowledge and experience in the pathology of a child and/or a specific diseased organ.

15.4 Patient Preparation

Patient preparation for CT of adult patients usually means obtaining informed consent, checking renal function and, for the gastrointestinal tract, instructing the patient about oral bowel contrast application or contrast enema. In children, preparation is usually more complex and is an important prerequisite for a successful examination (Table 15.3). Older children often want to be considered as individuals whereas in young children the preparation – beyond the patient herself/himself – often involves the physician, the nurse and the parents. They usually have a better approach to the child and are essential in convincing the child about the need for the examination, in informing about the procedure and its possible discomfort but also in staying with the child during the examination, or in calming by hand contact or conversation. Specially trained staff will site the intravenous line well in advance, will address the children properly and make them feel comfortable; an environment without machines and noise may meet the child's perceptions of the world and trigger trust. All actions avoiding pain and excitement and, thus, motion artefacts or even repeated scans should be considered to improve the quality of the examination and to control radiation exposure. Depending on the individual, medication, fixation for painless positioning, sedation, anaesthetic supervision or general anaesthesia may be appropriate. Many specialized centres, ours included, prefer propofol as medication; to avoid local pain at the injection site, it has to be preceded by injection of another local anaesthetic drug. General anaesthesia, while still used for young, retarded or handicapped children, is nowadays tolerated well, but it is increasingly possible to avoid it thanks to the speed of modern scanners. Exercising cooperation and respiratory apnoea within the scanner but without radiation is a useful, risk-free procedure that avoids repeated scans. Apnoea can mostly be achieved at the age of 5–7 years, and elder children can even cooperate with inspiratory apnoea. Below 5 years it is often wise to accept superficial continuous respiration. The test before the use of radiation will allow for individual adaptation of these age limits. And even in the same patient, depending on the mood and the atmosphere, cooperation may be possible one time and no longer achievable the next time.

Local, superficial, protective absorbing devices deserve special mention. They are available for the lenses of the eyes, the thyroid gland, the breast glands and the testes, and they are an efficient shield against external scatter radiation when the organ is outside the scanned area of the body (Beaconsfield et al. 1998; Brnic et al. 2003; Hidajat et al. 1996; Hohl et al. 2005; Price et al. 1999); of course, internal scatter will hardly be affected. Protecting organs located superficially within the area scanned is an alternative approach and must be used carefully since it might cause artefacts and lower the diagnostic quality (Fricke et al. 2003; Hopper et al. 1997). In our own experience, breast protection in adult women has not been as effective as suggested

Table 15.3. Patient preparation for paediatric CT

1. Decrease anxiety	– Inform where appropriate – Have an accompanying person in room – Provide calm environment
2. Avoid pain	– Site intravenous line well in advance – Immobilize – Sedate/anaesthetize/(intubate)
3. Exercise cooperation	In scanner, without radiation, exercise respiration, any specific cooperation expected
4. Apply local protection device	– Outside scanned volume (thyroid, breast, testes, lenses) – Organ protection within scanned volume (lenses, thyroid, breast, testes)

initially by Hopper, and it is rarely used in clinical routine. Fricke's group has reported better success in girls, keeping the absorbing material at a distance of around 2–3 cm from the skin by interposing a layer of foam, thus avoiding severe degradation of image quality. Testicular capsules are highly appropriate in shielding from indirect and direct exposure, and usually important information is not lost at the level of the testes. In contrast, the deep location of the ovaries basically excludes any local protection by an absorbing material.

15.5 Protocol Definition

15.5.1 Accept Noise as Long as the Scan is Diagnostic

The referring doctor and the radiologist basically want the best for the patient. Images at higher dose look nicer than those obtained at low dose, and if one equates nice to good one tends to prefer the beautiful higher dose images. This mechanism has favoured higher-dose practice over many years. Nowadays, radiologists and clinicians have to realize that *image quality cannot be the only criterion* when biological facts tell us that ionizing radiation may indeed induce cancer at a dose very close to the dose of one CT scan (in around 1‰ of small children). Unfortunately, it is not easy to balance an actual medical need with a rare statistical (stochastic) risk evident only within decades. Since we cannot easily quantify the risk, we should at least try to diminish it. Bringing the dose down to 50% mostly will not affect the diagnosis although the images will be slightly inhomogeneous. Often – of course depending on the organ and the medical question – a greater dose reduction will be tolerable. It is the radiologist's important task to go to the limits, i.e. to accept as much noise as the specific medical task allows (Cody et al. 2004; Ravenel et al. 2001; Shah et al. 2005; Vock 2005). The practical ways of simultaneously achieving dose reduction and *controlling the noise level* are discussed under points 2 and 3 (Table 15.4). The acceptable noise level can be defined by guidelines on *quality criteria* for specific medical imaging tasks, as initiated by the European Commission (European Commission 2000a). Whether post-processing using noise-reducing filters can be used in this situation without loss of sensitivity is still an open question (Kalra et al. 2004).

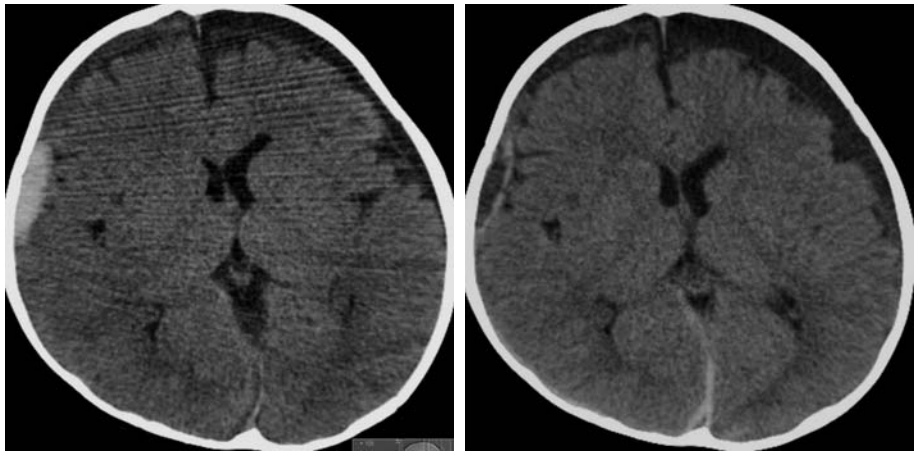
There is another way of reducing the dose and still maintaining the *S*/*N* ratio by post-processing. With modern scanners, while one usually does not want to lose *z*-axis resolution by prospectively scanning thicker slices, one can easily *acquire noisy thin slices* of 0.5–1.5 mm but simultaneously calculate *thicker images* of 2–6 mm, *used primarily for interpretation*. The thicker images have a good *S*/*N* ratio; the thin images still are used to look at critical details and to get 2D reformation and 3D analysis.

15.5.2 Optimize Scan Parameters Within the Axial Plane

Different scanners have different geometry and tube filtration, and slightly differing efficiencies of the detectors and data acquisition system, factors that usually cannot be influenced by the radiologist or technician. It is likely that the market competition will minimize these differences soon. It is also probable that *additional filtration* will be available for thin patients, decreasing the range of photon energies and therefore reducing the proportion of low-energy photons absorbed almost completely in the body, similar to the current experience in radiography and fluoroscopy. We are free to choose the kVp, the rotation time and mA settings. The *kVp* value needed goes with the diameter of the patient (Frush et al. 2002), and paediatric protocols provided by the manufacturer may suggest the appropriate kVp, mostly following the arguments discussed in Section 15.1 above. Figure 15.1 demonstrates that a lower tube voltage often allows improved image quality at the same or a lower dose. The shortest *rotation time* is mostly appropriate in paediatric CT; since with small objects the capacity of the tube and the acquisition system are not critical, this serves to minimize motion artefacts. Exceptions requiring slower rotation are the same as in adult patients but should be used restrictively. Defining the *tube current* (*mA*) needed is clearly the most critical and difficult choice. Again, general physical rules apply, and scanner-specific suggestions for different regions and ages have been proposed (Table 15.5). In practical work it may be important to realize that for every reduction of the patient diameter by 3.5 cm there is roughly 50% less absorption, and the current can be reduced accordingly in children.

Table 15.4. Protocol definition for dose reduction in CT of children

1	**Accept noise as long as the scan is diagnostic**
	– realize that in digital X-ray imaging noise reduction requires higher exposure – reduce mAs (and possibly kV) – reconstruct additional thick noise-reduced slices without increase of exposure
2	**Optimize scan parameters within the axial plane**
	– increase tube filtration (if available) – use maximal slice thickness appropriate for specific diagnosis – decrease kVp for thin objects – use shortest rotation time available (only few exceptions in children) – decrease baseline mA (CTDI) according to body diameter and composition – use *xy*-plane dose modulation to minimize CTDI
3	**Optimize scan parameters for volume coverage**
	– use representative volume sample when entire volume is not needed (by sequential scans with gaps) to reduce DLP – use spiral scan with pitch >1 (e.g. 1.5) to reduce DLP – use thicker collimation with overlapping reconstruction when thin slices are not needed – use *z*-axis dose modulation to decrease DLP – in the near future, use noise-defined automatic exposure control
4	**Scan minimal length**
	– be restrictive in defining uppermost and lowermost limits to keep DLP low – use localizing projection scan extending just minimally beyond scan limits
5	**Minimize repeated scanning of identical area**
	– avoid major overlap when scanning adjacent areas with different protocols – avoid non-enhanced scans unless specifically justified (e.g. for densitometry) – optimize the protocol to obtain all the information requested during one scan (e.g. contiguous 5-mm images and 1-mm HRCT images every 10 mm) – minimize number of scans in multiphase scanning to decrease DLP – in case of multiphase scanning, use shorter scan length for additional scans – use lower CTDI for non-enhanced or repeat scans unless high quality is needed – use minimal number of additional sequential functional scans to keep DLP low – minimize length of scans and fluoroscopy time in interventional applications – replace test bolus / bolus triggering by standard scan delay unless timing is very critical



a **b**

Fig. 15.1a, b. Influence of decreasing the voltage on the quality of a brain CT in a 1-year-old child with subdural haematomas of variable age. **a** Scan at 120 kV, 250 mAs, $CTDI_{Vol}$ of 45 mGy, DLP of 688 mGy·cm, estimated effective dose of 4.8 mSv. **b** Scan 2 days later at 100 kV, 330 mAs, $CTDI_{Vol}$ of 43 mGy, DLP of 613 mGy·cm, estimated effective dose of 4.3 mSv. Note the markedly improved contrast in this follow-up scan despite a slightly lower effective dose

Table 15.5. Suggested paediatric CT protocols

Weight (kg)	$CTDI_{Vol}$	kV	mAs	Rows	Comment	Reference
4.5–<9/9–<18			40/50	4	chest	Donnelly et al. (2001) Frush et al. (2002)
18–<27/27–<36			60/70		abdomen	
36–45			80			
>45–69			100–120			
>70			•140			
2.5–5 (<2 years)	6.7 (5.6)	80	72	4 × 2.5	abdomen	Verdun et al. (2004)
5–15 (2–6 years)	9.4 (12)	100	56		pitch 0.75	
15–30 (6–14 years)	15.9 (14)	120	64			
30–50 (14–18 years)	24.5(23.5)	120	96			
<15		120[a]	14/25	4	chest/abdomen	Suess and Chen (2002)
15–24			23/41			
25–34			32/66			
35–44			45/99			
45–54			68/132			
>54			90/165			
<15		120[a]	17	16	chest	Fishman (2006)
15–24			20–40		abdomen	
25–34			30–50			
35–44			50–80			
45–54			70–100			
<15			30–40			
15–24			50–65			
25–34			65–80			
35–44			90–110			
45–54			120–140			
	$CTDI_w$	DLP	eff. dose		DRL brain/chest	Shrimpton and Wall (2000)
<1	40/20	300/200	2.7/6.4[b]			
5	60/30	600/400	2.4/7.2[b]			
10	70/30	750/600	2.3/7.8[b]			
<1	20/20	330/170	12.5/5.4[b]		upper/lower abdomen	
5	25/25	360/250	7.2/4[b]			
10	30/30	800/500	12/7[b]			

Dimensions – $CTDI_{Vol}$, $CTDI_w$: mGy; DLP: mGy·cm; eff. Dose: mSv.
[a] At 80 kV same *S/N* ratio at 50% mAs. [b] Eff.dose: Shrimpton et al. (2005).

Furthermore, based on the minimal risk of modern contrast agents, it might be appropriate in children to replace a native scan by a contrast-enhanced scan, using a lower mAs setting in view of the improved contrast. Unfortunately, no standards of *acceptable noise* with a specific reconstruction algorithm needed in different medical indications have yet been described. Definition of the desired noise level will facilitate scan protocol selection in the near future thanks to interactive *dose modulation* mechanisms that are currently being used in their first generation; since these options for automatic dose reduction are mostly effective in spiral volumetric scanning they will be discussed below with the approach to volume coverage.

$CTDI_w$, the CT dose index (CTDI) weighted for central and peripheral locations, is the entity that reflects the selection of parameters during one rota-

tion, such as used in sequential axial scanning, but also one of the most important parameters in spiral scanning. It is most helpful for comparing the relative exposure due to different protocols. However, it is clearly based on a round phantom and neither respects the diameter, the shape or the composition of the individual patient.

15.5.3 Optimize Scan Parameters for Volume Coverage

The way we scan the volume to be studied is the single most important determinant of radiation exposure in CT protocol definition. The term used to characterize volume exposure is the *dose–length product* (*DLP*), a parameter directly derived from the product of the $CTDI_w$ and the length of the scan. DLP has the same restrictions as $CTDI_w$ in being a physical parameter not adapted to the individual patient's body. But DLP and $CTDI_w$ have the important advantage of being measurable and, thus, offered by the scanner at the end of a study or even earlier for prospective planning. Since the literature gives factors to translate DLP values into effective dose (Chapple et al. 2002; Shrimpton et al. 2005), DLP as the only practical risk parameter must be checked regularly by both the radiologist and the technician; CT doses can therefore be estimated both for the individual patient (Table 15.6) and the population (Pages et al. 2003).

Historically, with *sequential CT* contiguous slices were usually measured, giving a more or less homogeneous dose distribution that we define as 100%. To improve *z*-axis resolution, one had to use some overlap; an overlap of 20% (e.g. slice 5 mm, distance between slices 4 mm) increased exposure to 120%. On the other hand, for HRCT in diffuse interstitial disease of the lung, scanning a sample of 10% of the organ (1 mm slice, distance between slices 10 mm), often considered adequate, reduces exposure to 10%. The introduction of *spiral CT scanning* with a *single row of detectors* avoided overlapping scanning, leaving exposure at 100% in the example cited, even when images were reconstructed at smaller distances of 1–4 mm; of course, this was only true with identical parameters and when table movement during one rotation was exactly the value of the slice collimation; this basic condition was defined as a *pitch* of 1 and, in consequence, a movement of twice the collimation was called a pitch of 2. For this type of scanner, it was therefore attractive to increase the pitch in order to reduce radiation exposure (Donnelly et al. 2001), with the only restriction that high pitch values caused a major thickening of the resulting slice above the collimation. Although not important for long *z*-axis volume scans, spiral scanning means a small additional exposure outside the defined volume during the first and the last rotation of the gantry since data are incomplete and have to be discarded partially.

Current *multirow detector scanners* have increased the options for protocols enormously but also share a disadvantage in performing the HRCT protocol of the lung and other applications where partial sampling of a volume would be medically adequate. They may have to scan two or four slices instead of the single one needed, and collimation at the detector may cause a loss of signal. Aside from this restriction, however, they are mostly used in the spiral mode and have enhanced the speed and the resolution of CT scanning, avoiding the problem of tube heating and offering real *isotropic data* for 3D analysis. The new scan geometry needs more complex image calculation to correct for the diverging beam of the outer detectors but the operator does not have to take care of this modification. Also, the pitch factor has become less important since the increased speed offers other ways to cover a large volume and still to control exposure; similarly, combining the information of different detector rows for the reconstruction of one image has overcome the problem of slice thickening, as seen with early spiral scanners and higher pitch factors.

Table 15.6. Effective dose estimated from dose–length product

Age (years)	Head	Neck	Chest	Abdomen/ Pelvis
0	0.011/0.027	0.017/–	0.039/0.034	0.049/0.040
1	0.007/0.008	0.012/–	0.026/0.021	0.030/0.024
5	0.004/0.004	0.011/–	0.018/0.014	0.020/0.016
10	0.003/0.003	0.008/–	0.013/0.011	0.015/0.014
15			–/0.015	0.015/0.009
Adult	0.002/0.003	0.006/–	0.014/0.009	0.015/–

Numbers give normalized effective dose per dose–length product (mSv per mGy·cm).
First number from Shrimpton et al. (2005)/second number from Chapple et al. (2002).

The increased power of modern scanners has mostly eliminated hardware restrictions of older generations and made it easy to define protocols with a high radiation exposure, reaching the range of complex angiographic or fluoroscopic studies. This has increased the pressure of using any solution available to reduce radiation exposure. Current CT scanners offer one or several of the following options:

XY-plane dose modulation: this option was introduced to overcome the physical problem that the human body is neither round nor of homogeneous density (Greess et al. 2004). To achieve the same *S*/*N* ratio, less radiation is required in the direction of the smaller diameter (anteroposterior at the level of the shoulders, *y*-axis) than in the direction of the larger diameter (left to right at the same level, *x*-axis), and this difference is exaggerated by the presence of more bony mass in the *x*-axis. Modulation of the tube current according to the angle of the tube position around the patient is the logical solution; it is achieved either by estimating the global absorption at all *z*-axis positions from an anteroposterior and a lateral localizing projectional view, or by using the information obtained during one rotation to interactively adapt the tube current for the same angle during the next rotation (Suess and Chen 2002). *xy*-plane dose modulation reduces the nominal mAs by around 20%–40%, depending on the body region, and it is generally appropriate to use it. Specific new applications of *xy*-dose modulation are appropriate for the heart and, maybe, the breast gland. This means prospectively ECG-triggered lower mA values during the phases of the heart that are not used for reconstruction and higher mA values during important phases, such as mid- to late diastole. A similar approach might be used to decrease the radiation exposure of the breast gland in chest CT of young women by decreasing mA when the tube is located in front of the patient and – for compensation – by increasing mA when the tube is at their back.

z-*axis dose modulation*: as for the axial plane, physically in the longitudinal axis of the body (*z*-axis) the radiation needed for an adequate *S*/*N* ratio will vary with the diameter and density of the patient. For example, in cervicothoracic scanning, the cervical area and the lower chest require much less of a dose for a given image quality than the thoracic inlet and shoulder area. Similarly, until recently, one had to interrupt scanning at a level between physically different adjacent body areas; e.g. to use a lower radiation exposure for the upper than the lower abdomen, one had to stop the upper scan at the pelvic rim and to start another scan with modified parameters for the pelvis, often with a significant technical delay. Modern scanners allow for adapting the tube output during one single scan in this and other clinical applications. The option of *z*-axis-dependent dose modulation is steered again either from the localizing view or interactively; it is clearly welcome to reduce radiation exposure and should be used generally (Tack et al. 2003).

It must be mentioned that dose modulation is an important step towards the final goal of *noise-defined automatic exposure control*, and that the solutions implemented in current scanners may have rules for adaptation not easily understood by the user; one therefore has to be careful not to run into dose augmentation, e.g. by starting the scan at a level with low dose requirement at a nominal mAs value selected for the thickest scan level to be covered. Software tools will simplify the choice in the near future, e.g. by offering a selection of images with different noise.

Control of noise in the image is one approach whereas observation of the DLP per examination is another practical approach. Since in CT examinations the DLP is a good representative of effective dose to a specific area of the body, *diagnostic reference levels* (*DRL*) indicating an upper DLP not to be exceeded in typical clinical tasks are the practical solution (Shrimpton and Wall 2000; Wall 2001). DRLs correspond to the third quartile (75% lower values obtained from a population with the same examination). They do not represent an absolute barrier; however, they should be defined for specific body areas, according to the weight and the medical task. Since the DLP is available immediately during the study, each radiologist can prospectively plan the DLP to stay within the specific DRL or, exceptionally and with an appropriate justification, to exceed it for a concrete reason.

15.5.4 Scan Minimal Length

This rule applies both for the scout view and the rotational scan since there is really no value in going beyond the tissue volume where pathology is suspected. It has to be followed at two levels: the referring physician and the radiologist have to find

a compromise about the minimal *body areas to be investigated*; the radiologist and the technician have to fine-tune the *upper and lower end of the examination* (Donnelly et al. 2001). In a lung scan, there is no reason to include the entire thoracic inlet with the thyroid gland as well as the upper half of the abdomen with multiple radiosensitive organs (Campbell et al. 2005). In a pelvic scan of a boy, there is hardly ever a medical reason to include the testes. Independent of the organs included, any increase in scan length will proportionally increase energy deposition and the biological effects of ionizing radiation. While other rules are the primary responsibility of the radiologist, the technician and her/his experience are most critical for this rule. In routine scanning, it is simply not justified to extend the length beyond the minimum required. For example, a chest scan has to cover the lowest part of the costophrenic sulcus and – in neoplastic disease – the adrenal glands; any inclusion of more abdominal structures will induce non-justified radiation exposure to sensitive organs.

For two reasons, the rule should be used less strictly for the localizing than for the sectional scan. First, radiation exposure – although often neglected in dose estimation – is small during a localizing projectional view, usually contributing a very low percentage to the global exposure. Second, the localizer has to include the starting and ending levels of the spiral scan and is a prerequisite for properly limiting the scan length to the minimum needed in the specific medical situation.

15.5.5 Avoid Non-Justified Multiple Scans of the Same Area

Numerous opportunities exist with the current powerful scanners to scan the same volume of the body twice or even several times. Since there is no longer a technical restriction, multiphase studies can be performed without tube heating or data overflow.

Perhaps the most frequent neglect of this rule happens when two adjacent body areas are scanned with different protocols and a large overlap. The obvious example for this may be cervicothoracic scanning in malignant lymphoma; while the head and neck scan is planned on a lateral localizer, the scan of the trunk is planned on an anteroposterior localizer, and large overlaps at the thoracic inlet often cause multiple scanning of sensitive organs, such as the thyroid gland.

A number of *medical reasons* may require different types of repeat scans of the same area:

- correct timing of scans, using a test bolus or repetitive scanning of one plane at low dose for bolus triggering of the proper diagnostic scan
- dynamic enhancement studies including arterial, parenchymal, venous and/or excretion phases of organs, such as the kidney or liver
- functional lung scans to detect air trapping in inspiration and expiration (in young children unable to cooperate this may also be achieved by scanning in right and left lateral decubitus position)
- supine and prone scans for demonstrating positional gravitational effects
- CT-guided intervention, with or without fluoroscopy
- screening with thick slices and subsequent detailed analysis with thin slices
- exceptionally in childhood: native and contrast-enhanced scan after intravenous bolus injection.

Some but by no means all of these technical possibilities are justified in medical problem solving, and it is probably the most difficult task of the resident in radiology to think of all these potential options and not to overuse them in view of radiation exposure. For example, renal CT may often be adequately performed with a single scan after a two-phase injection of the contrast agent, showing both the parenchyma and the pelvicalyceal systems. It is quite clear that *double scanning* means *twice the radiation exposure* as long as the same parameters are used, and even more scans will increase exposure proportionally. Aside from medical experience, a few general guidelines may help to appropriately select the number of scans. First of all, and again, the individual *situation of the current patient* must be checked. Will any of the repeat scans help this patient? Will it influence the management or even the outcome? Is it cost-efficient when we add radiation exposure to the financial cost? Second, *repeat scans* can often be *limited to a smaller volume* or performed at *lower dose* that will not hide the additional information expected. Third, fixed standard scan timing can often replace individual triggering or a test bolus unless cardiovascular disease is present and timing very critical. Fourth, while CT fluoroscopy is a very helpful tool in cases of difficult access, other biopsy methods or drainages can often be done under CT image control

or even under ultrasound guidance. Fifth, in the lung one single scan can usually be used to obtain all the information needed: using thin detector rows of around 1 mm will allow one to calculate both thin HRCT sections at any *z*-axis level and thick 5-mm scans, as needed for tumour search or mediastinal analysis; for reformations and 3D post-processing, continuous and overlapping images can be prepared from the same raw data.

In conclusion, CT is characterized by a significantly higher radiation exposure than radiography. Based on its excellent diagnostic potential in a range of medical situations its use has significantly increased in children. However, due to the increased biological impact of radiation exposure in children, paediatric CT examinations should follow a strict justification and optimization by careful selection of protocol parameters as well as the range. The steps discussed above help the radiologist to apply the ALARA principle when scanning children (Slovis 2003).

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