REVIEW ARTICLE

Radiation Protection in Pediatric Radiology

Gerhard Alzen, Gabriele Benz-Bohm

SUMMARY

Background: The German Federal Law on Radiation Control contains no special provisions for X-ray studies in children and adolescents, even though exposure to ionizing radiation must be kept especially low in young persons, because their tissues are highly radiosensitive. Children, who have many years left to live, are more likely than adults to develop radiation-induced cancer; also, as future parents, they are at risk for passing on radiation-induced genetic defects to the next generation. Whenever possible, radiological studies on children and adolescents should be of a type that does not involve ionizing radiation, such as ultrasonography or magnetic resonance imaging. Pediatric conventional X-rays and computerized tomography (CT) require special examining techniques and protocols that are adapted to the patient's age and to the indication for the study.

Methods: We selectively review the literature on pediatric dose reduction and discuss our own investigations on the subject as well.

Results: The essential technical prerequisites for lowering the dose of ionizing radiation in conventional X-ray studies include the proper setting of tube voltage, the use of tube filters, suitable patient positioning and fixation, variable use of a scattered-radiation grid, and a modern storage-plate system. In CT studies, the use of age- and indication-adapted protocols can lower radiation exposure by as much as 95%.

Conclusion: There are now many ways to lower the exposure of children and adolescents to ionizing radiation without sacrificing diagnostic reliability. The main factors in lowering exposure are proper attention to clinical indications, the use of special X-ray protocols, the use of alternative imaging studies without ionizing radiation wherever possible, and the expertise of the examiner.

► Cite this as:
Alzen G, Benz-Bohm G: Radiation protection in pediatric radiology.
Dtsch Arztebl Int 2011; 108(24): 407–14. DOI: 10.3238/arztebl.2011.0407

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The use of ionizing radiation in humans is uniformly regulated, for children as well as adults, in the German Federal Law on X-Ray Examinations, extensively revised in its most recent, 2002, version and the 2001 edition of the German Federal Law on Radiation Control (e1, e2).

Tissue radiosensitivity

Tissues with high mitosis rates are fundamentally more vulnerable than inactive tissues, as DNA metabolism is damaged by radiation (e3). In an adult body, only tissues subject to high levels of cell turnover throughout the individual's life are still exposed to greater risk. The radiation risk is therefore highest in infancy and early childhood, in line with general growth patterns, and in adolescence it gradually approaches the risk to which adults are exposed *(Figure 1)* (1–4).

Children's and adolescents' tissues also have a higher water content than adult tissues. This means that more radiation is absorbed and dispersed, so a higher dose is needed to penetrate a layer of tissue of the same thickness.

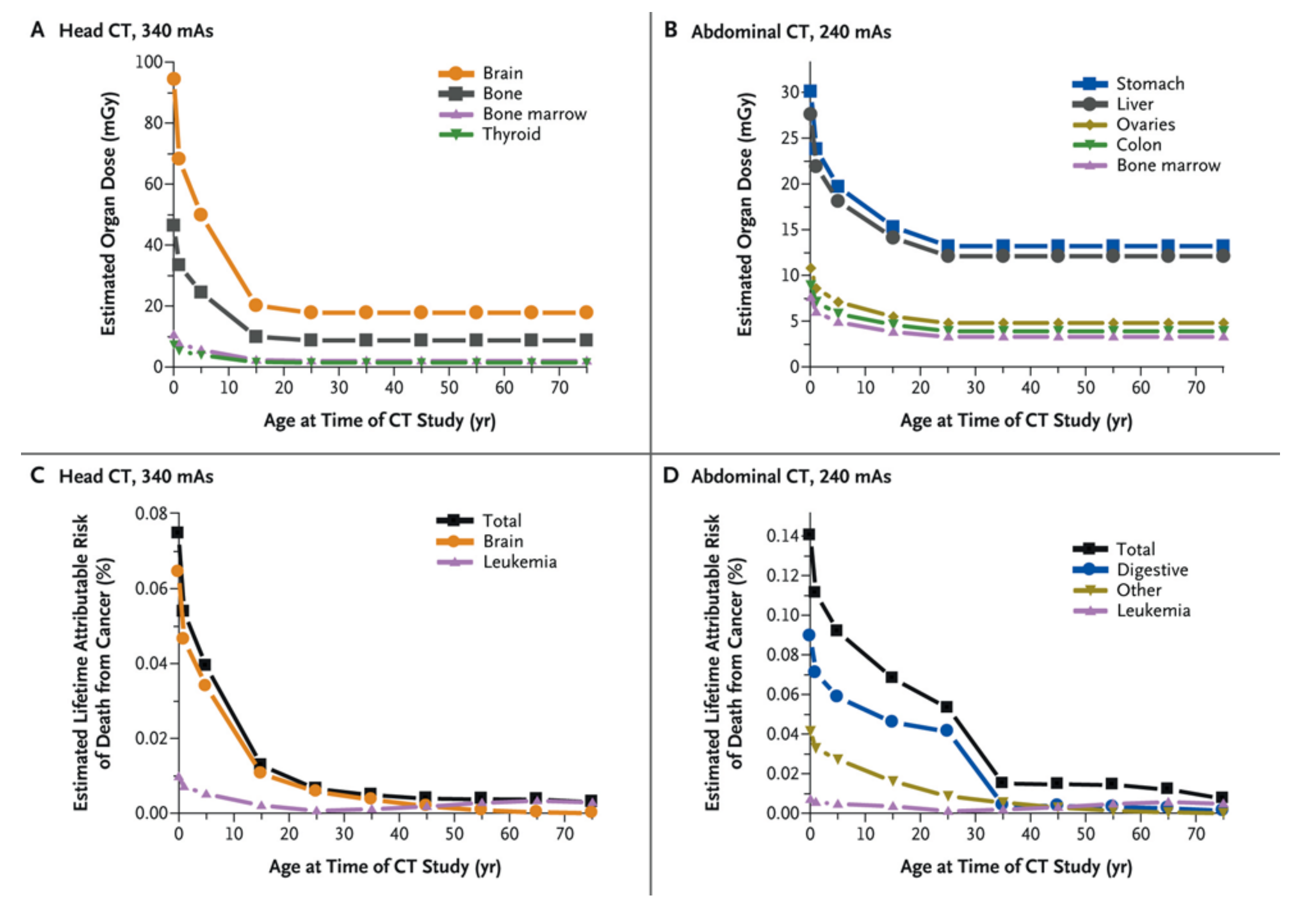
Life expectancy

As radiation-induced malignant lesions remain latent for years *(Table 1)*, children and adolescents are prone to experience them (5, 6, e4). If we also consider that the probability of requiring X-ray diagnostics is highest before the age of 1 year and falls steadily until the age at which children start school, the differences between adult and pediatric X-ray diagnostics become even clearer. At school age and then working age, with every year of life, the average need for X-ray diagnostics in the population as a whole increases slightly. The need for X-ray diagnostics remains low for several decades and does not increase again until old age, or when a specific individual develops a life-limiting condition (e5, e6). As a result, the individual and collective radiation risk is particularly high for infants and small children.

Genetic risk

If children and adolescents' genes are damaged by ionizing radiation, their descendants will suffer higher rates of deformities. Little is known about the scale of this risk (1): Too many other teratogenic noxa affect the overall risk. The number of deformities in neonates is not the only reflection of the total mutagenic risk: in

FIGURE 1



Estimated organ doses and lifetime cancer risks from typical single CT scans of the head and the abdomen.

Panels A and B show estimated typical radiation doses for selected organs from a single typical CT scan of the head or the abdomen. As expected, the brain receives the largest dose during CT of the head and the digestive organs receive the largest dose during CT of the abdomen. These doses depend on a variety of factors, including the number of scans (data shown are for a single scan) and the milliamp-seconds (mAs) setting. The data shown here refer to the median mAs settings reported in the 2000 NEXT survey of CT use. For a given mAs setting, pediatric doses are much larger than adult doses, because a child's thinner torso provides less shielding of organs from the radiation exposure. The mAs setting can be reduced for children (but is often not reduced); a reduction in the mAs setting proportionately reduces the dose and the risk. The methods used to obtain these dose estimates have been described elsewhere,20 but software that estimates organ doses for specific ages and CT settings is now generally available.

Panels C and D show the corresponding estimated lifetime percent risk of death from cancer that is attributable to the radiation from a single CT scan; the risks (both for selected individual organs and overall) have been averaged for male and female patients. The methods used to obtain these risk estimates have been described elsewhere. The risks are highly dependent on age because both the doses (Panels A and B) and the risks per unit dose are age-dependent. Even though doses are higher for head scans, the risks are higher for abdominal scans because the digestive organs are more sensitive than the brain to radiation-induced cancer.

(N Engl J Med 357; 22:2277–84)

many cases in which a deformity is diagnosed prenatally, pregnancy is terminated. It is also impossible to reliably determine the number of early abortions that may be due to severe congenital malformations.

Bodily proportions and at-risk tissues

The proportions of a child's body differ considerably from those of an adult's body. In general, an infant's body is shorter and more broadset than that of an adult. If the trunk of an infant or small child's body is X-rayed, the body shape inevitably means that larger areas of the body lie within the radiation field, or at least directly adjacent to it, and are therefore more affected by scattered radiation.

There are also differences in the location of particularly at-risk tissues such as hematopoietic bone marrow. In adults, 74% (spine, ribs, pelvis) is located in the skeleton or the trunk, and only 9% in the extremities (7). In adults, 8% is located in the cranial bones; in infants, 27%. In infants, 29% is located in the skeleton of the trunk and 35% in the extremities. This means that infants have large proportions of hematopoietic bone marrow in all parts of the body, including the extremities.

Imaging in pediatric radiology

The most essential difference between adult and pediatric radiology is the different disease spectrum of children and the resulting clinical questions regarding imaging. Together with efforts to perform diagnostic procedures which are as gentle but as reliable as possible, strict indication guidelines for children are one of the most essential factors in radiation protection (e5, 8, 9).

Targeted, or, if necessary, staged, diagnostic procedures must be arranged with the doctor requesting the procedures, on the basis of reliable clinical information. Thanks to ultrasonography and magnetic resonance imaging, procedures with high levels of radiation exposure such as computed tomography and angiography need only be indicated in a small number of cases.

In a German pediatric tertiary care hospital, ultrasound examinations account for approximately 70% of all pediatric radiological procedures performed and are used both in addition to and as an alternative to other procedures. Ultrasonography can be used to find answers to many clinical questions regarding almost all organ systems from primary diagnosis to progress evaluation.

The best radiation protection for children and adolescents is doctors with optimum training in ultrasonography: doctors who are generally able to answer questions using their examinations, rather than raising new ones. Part of using ultrasonography skillfully is to know its limitations, and if necessary using other imaging modalities in a targeted way.

The radiation doses associated with the radiological procedures available today differ by a factor of 10^3. Modern storage-plate systems make it possible to capture images with very low radiation doses and high resolution in plain film radiography (e7, e8). Computed tomography, meanwhile, has experienced huge technical innovations in the last 10 years:

- Shorter procedure times
- Increased image quality
- Many possibilities for secondary image processing.

At the same time, however, the dose of radiation can increase enormously.

The most common examinations performed in pediatric radiology are plain film radiography procedures such as X-rays of the chest and individual regions of the skeleton. They account for most exposure to radiation related to medical procedures (10). Although the individual's radiation risk usually remains low, the collective radiation risk is considerable. Because of the frequency with which these X-ray procedures are performed, every effort must be made to provide radiation protection and effectively standardized image-capturing techniques with the lowest possible doses.

The increase in computed tomographies at all ages is a major problem (11). Although many CTs could be replaced by MRI, the fact that MRI is more time-consuming and expensive, machines are less available, and uncooperative patients need to be sedated restricts its use.

Radiation protection measures in plain film radiography

The optimum dose for an X-ray examination should correspond to the ALARA (as low as reasonably achievable) principle (12–16).

TABLE 1

Average latency following radiation exposure and the probability of developing a malignant lesion*

Malignant disease	Latency
Leukemia (AML, CML)	2 to 25 years
Breast cancer (highest risk if exposed to radiation aged 10 to 19 years)	15 to 40 years
Sarcoma after high-dose radiation exposure	<1% but risk highest in children
Thyroid cancer	10 to 40 years

AML: Acute myeloid leukemia; CML: Chronic myeloid leukemia
*Modified according to (5, 6)

Generator

X-ray generators convert alternating current into direct current. Older generators (1, 2, 6 and 12 pulses) produce a direct current that also possesses a ripple of varying strength. This lengthens the switching time. At the same time, the proportion of weak radiation that is of no use in imaging but increases the dose rises. Ideal results are achieved using high- and medium-frequency generators.

Tube voltage

The higher the voltage selected, the more penetrating the radiation. As the target is thinner in children, the absolute dose of radiation needed is lower than for adults. Only a small amount of radiation is absorbed into the body and the necessary dose reaches the imaging system (film, storage plate, or image intensifier) quickly. The voltage used to obtain images of the trunk should therefore not exceed 65 kV. Pediatric radiology requires X-ray machines able to provide the necessary short switching times with sufficient consistency, even with low target thicknesses. In adolescents with thoracic diameter greater than 15 cm, images are captured using a high-kilovoltage technique (125 kV), as in adults.

Tube filters

X-ray examinations of adults must be performed with a tube filter of at least 2 mm aluminum. For children and adolescents, an additional tube filter of 1 mm aluminum (Al) and 0.1 to 0.2 mm copper (Cu) must be used. The authors' research has shown that with a modern storage-plate system the tube filter can be increased to 1 mm Al + 0.2 mm Cu and the surface dose simultaneously halved with no negative effect on image quality (17, 18, e7). This approach should not be used with a conventional film–screen system, because when combined with the high tube voltage the images captured have very little contrast and are therefore not of sufficient quality for diagnosis.

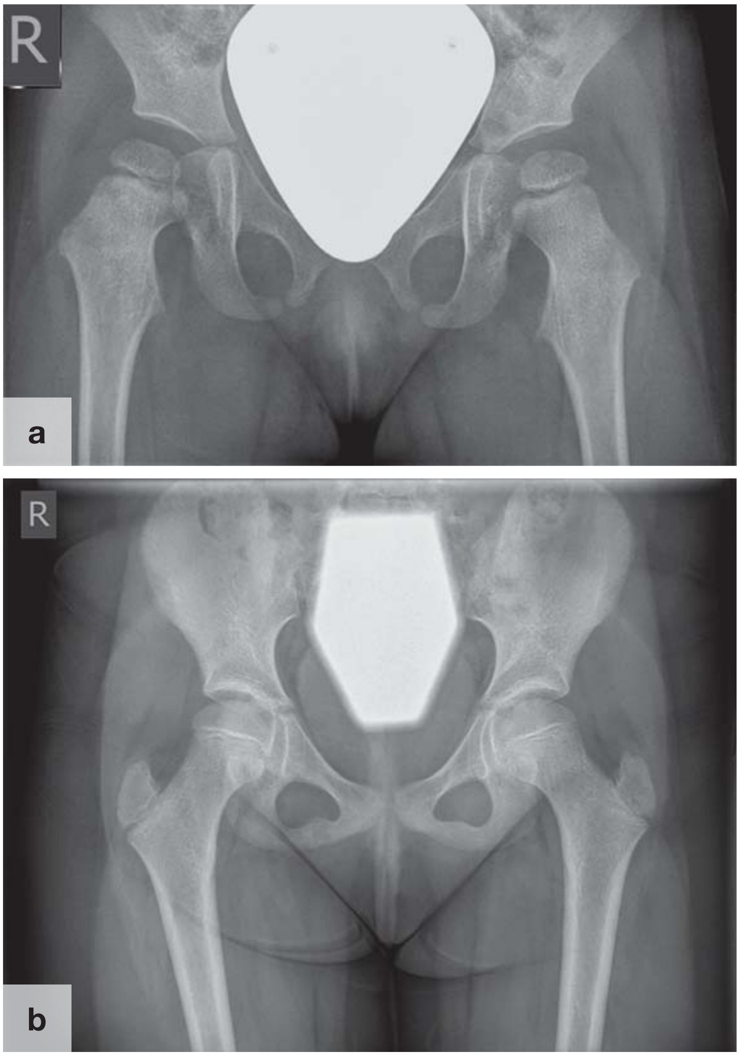


Figure 2: Examples of radiation protection in hip X-rays

a) X-ray of a girl aged 2 years, 9 months. Accurate positioning of gonad protection and good collimation.

b) X-ray of an 8-year-old girl. The image extends too far in a cranial direction. The gonad protection used is both unsuitable and incorrectly positioned.

Collimation

X-ray images must be as well collimated as possible. This reduces primary and scattered radiation. Even if poor collimation does not expose any additional parts of the body, the dose is still increased as a result of the higher proportion of scattered radiation. With images involving smaller radiation fields, a significant divergence between the radiation field and the sighting device can become apparent. Correct gonad protection must therefore be used *(Figure 2a, b)*. With X-ray examinations using machines in which the tube is above the table the field size can also be adjusted using the sighting device, making it possible to use a considerably lower dose than with machines in which the tube is below the table *(Figure 3)*.

Patient position

The patient should be in as close contact as possible with the imaging equipment, so that none of the dose of radiation is wasted by escaping from the body. X-ray machines with as short a distance as possible between the table and the cassette or the table and the image intensifier input level should therefore be preferred. For images with no scattered-radiation grids, the patient should lie directly on the cassette. Unlike adults, in infants and small children thoracic images are captured using an anterior-posterior (AP) projection, because more hematopoietic bone marrow (vertebrae, ribs, shoulder blades) is located in the dorsal part of the body.

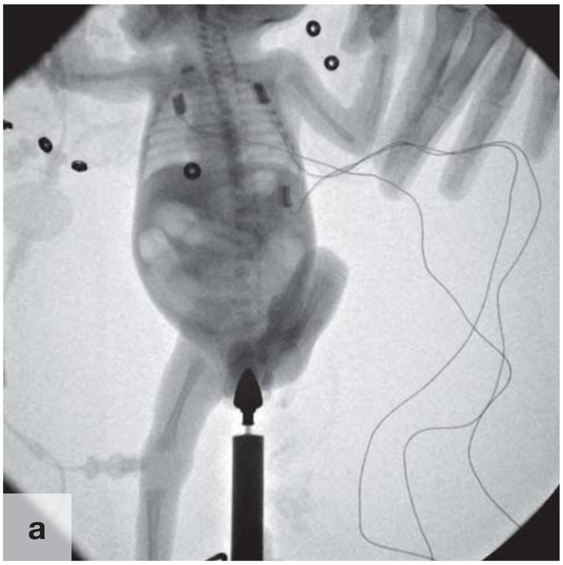
Fixation and orthograde adjustment of the image should not involve anyone holding the child. The use of infant holders and other fixation devices is compulsory, even if it is not popular with parents. However, if it is necessary for someone to hold the child, a parent should preferably be asked to do this. Otherwise it naturally falls to individuals who are professionally exposed to radiation according to Section 31 of the German Federal Law on X-Ray Examinations to perform this duty (e1).

Scattered-radiation grids

The use of scattered-radiation grids is not recommended with thin objects. The proportion of scattered radiation in such cases is so low that no discernible improvement in resolution can be achieved. The use of a scattered-radiation grid suitable for pediatric radiology (minimum thoracic diameter 15 cm) with ratio r = 8/36 gives a dose twice as high as when no grid is used. The grids usually used in adult radiology (r = 12/40) are designed for body weights over 100 kg. If they are used for imaging, four or five times the dose needed for an image without a grid is required, depending on the tube voltage and field size. If small targets are X-rayed using this kind of grid, the switching time is so short that the moving grid records its own image and so has a negative effect on image quality.

Image-capturing systems

Film–screen systems in sensitivity class 400 to 800 are recommended for pediatric radiology. Newer storage



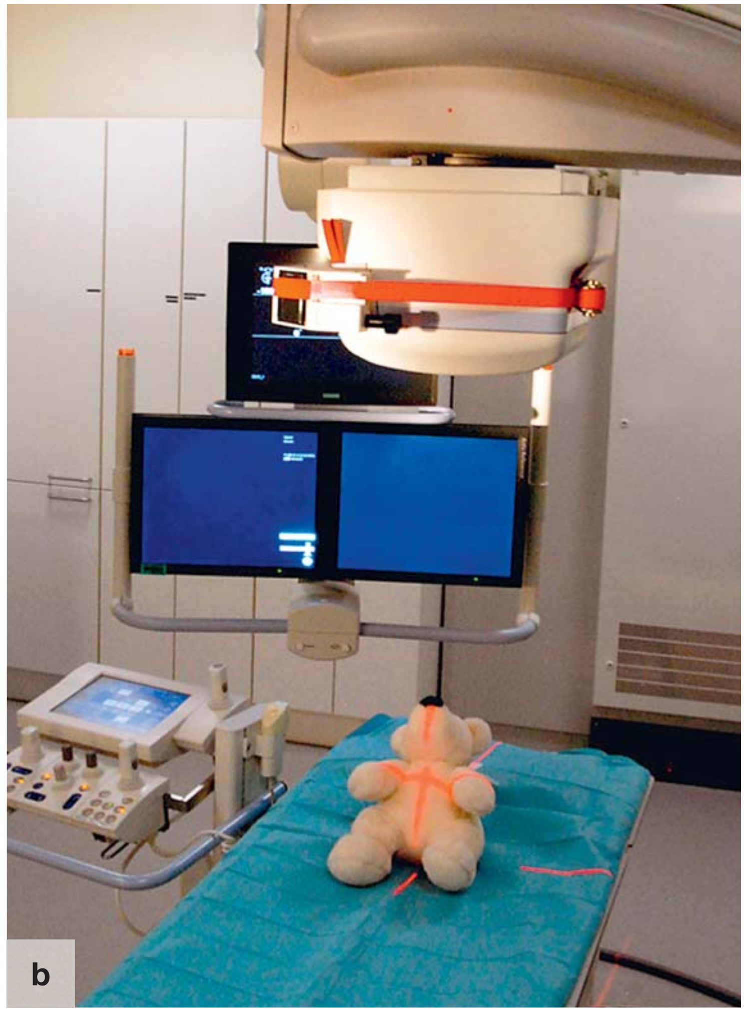


Figure 3: Radiation protection in X-rays

a) X-ray with image-intensifying input field open as far as possible, thanks to the manufacturer's programming of the machine. The examiner must use his/her own judgment to set the necessary size of the field before performing the examination.

b) There is no sighting device, which would be advisable here. Laser crosshairs are used to center the field, in order to achieve better orientation (authors' modification of the Axiom Artis machine manufactured by Siemens. Photo: Claudia Schad).

plates achieve excellent levels of detail for a given dose, or make it possible to reduce the dose, for example using additional filters, without affecting resolution *(Table 2)*. Older storage plates require doses up to 30% higher than film–screen systems in sensitivity class 400 and should therefore not be used for children. Flat panel detectors also perform well with low doses of radiation.

Controlling doses of radiation in X-ray examinations

Alongside equipment-based and patient-based methods of reducing the dose of radiation, the examiner's experience plays a decisive role in X-ray examinations in children, with a very substantial effect on the length of time needed for examinations and the quality of field collimation. The following are essential technical requirements for lowering radiation dose and should be borne in mind when purchasing an X-ray machine for children and adolescents:

- Machine in which the tube is above the table (optional: C-arm with tube that can be set to AP or PA position)
- Pulsed radiation (ideally grid-controlled)
- Removable scattered-radiation grid to examine small targets
- Exposure parameters adjustable with no prior radiological examination
- Field positioning and collimation possible using the sighting device, so that only minor adjustments are needed during radiological examination
- Last image hold (LIH)
- Wedge filter collimation with electronic positioning on a fixed image for digital subtraction angiography.

Radiation protection during computed tomography

The introduction of multislice machines with very short rotation times considerably increased the speed of examinations and reduced contrast substance use. Many studies were conducted into how to optimize examination protocols for adults (e9–e11). Today very high image quality can be achieved using a higher dose of radiation. As the associated radiation risk must be considered in children, in addition to image quality,

TABLE 2

Doses of radiation (dose-area product, DAP) needed for plain film radiography examinations in children*

Procedure	Age (years)	Dose needed according to the Department of Pediatric Radiology, Giessen (DAP) [µGym^2]	Diagnostic reference values (DRVs) [µGym^2]
Head AP	<1	7 to 8	30
	1 to 5		40
Head lat.	<1		30
	3 to 7		
Chest AP	Premature infants	0.3	0.3
	Neonates		0.8
	<1		2
	1 to 5	1.1	3
	6 to 12	2.7	4
Chest lat.	3 to 7	1.1	7
	8 to 12	2.7	8
Abdomen	<1	0.3	25
	3 to 7	0.2	50
	8 to 12	0.6	60
Pelvis	1 to 5	2.3	25
	6 to 12	6.6	30
MCU	Neonates	1.0	60
	<1		90
	1 to 5	2.0	120
	6 to 12 years	3.0	240

*Using a modern storage-plate system (Agfa, DX-S) and taking all possible measures to reduce the dose according to the current diagnostic reference values of Germany's Federal Office for Radiation Protection (Bundesamt für Strahlenschutz) (17, 18, 22, 23, e7)
MCU: Micturating cysto-urethrogram

suitable adapted examination protocols must be developed and cannot be altered at will (19).

Alongside general factors that affect the radiation dose, there are also considerably complex correlations regarding the use of various multislice machines. Because of the smaller target diameters involved, significantly smaller amounts of radiation (mAs) can be used for CT scans in children with no loss of quality. As a general rule, for pediatric examinations at 120 kV the formula mAs = (body weight [kg] + 5) × f has been established for various manufacturers' 16-slice CT machines. The recommended value of *f* varies according to the part of the body: chest *f* = 1, abdomen *f* = 1.5, head *f* = 2–5 (20, e10, e12).

When comparing scan protocols for CT machines made by different manufacturers, it is advisable to refer to the volume CT dose index (CTDI vol), which is stated on all modern CT machines. The CTDI vol includes several different machine parameters. Limiting scan length to the time necessary for diagnosis has a positive effect on the dose-length product (DLP), another objective measure of dose *(Figure 4)*. Recommendations for examinations should therefore include an anatomical definition of the area to be scanned and the DLP if possible. Overranging should also be considered. Overranging is the need to perform a 180° turn at the beginning and end of a spiral scan, in order to achieve complete image reconstruction. The shorter the area to be scanned, the more significant these additional parts of the body, which are also exposed to radiation. The latest machines have dynamic collimation that automatically makes visible the area exposed to overranging at the beginning and end of a spiral scan, making it possible to reduce the dose of radiation considerably. In children, due to short scan times, the dose can be reduced by up to 25% (e13) *(eTable 1)*.

Adapting examination parameters to each individual patient and clinical question requires extensive experience if the examination is to be appropriate for children. The image quality necessary in each case must be determined and the CT machine must be appropriately configured. The use of an image gallery containing example scans of patients at different ages enables examination parameters to be adjusted to individual patients, in line with the specific information needed from the scan, for each machine. Using simulations, the example images can be shown with different doses (11). In a clinical evaluation of this method, a dose reduction of more than 60% was achieved in abdominal and pelvic examinations as compared to examination protocols that had already been optimized for pediatric examinations (21, e12).

Planning examinations for individual patients requires a precise indication and close cooperation with the referring physicians. Only when the question to be answered is clear can the most effective radiation protection be provided, minimizing or even avoiding exposure to ionizing radiation. A CT scan can often be optimized or even avoided using a previous ultrasound or MRI examination (in the authors' pediatric radiology

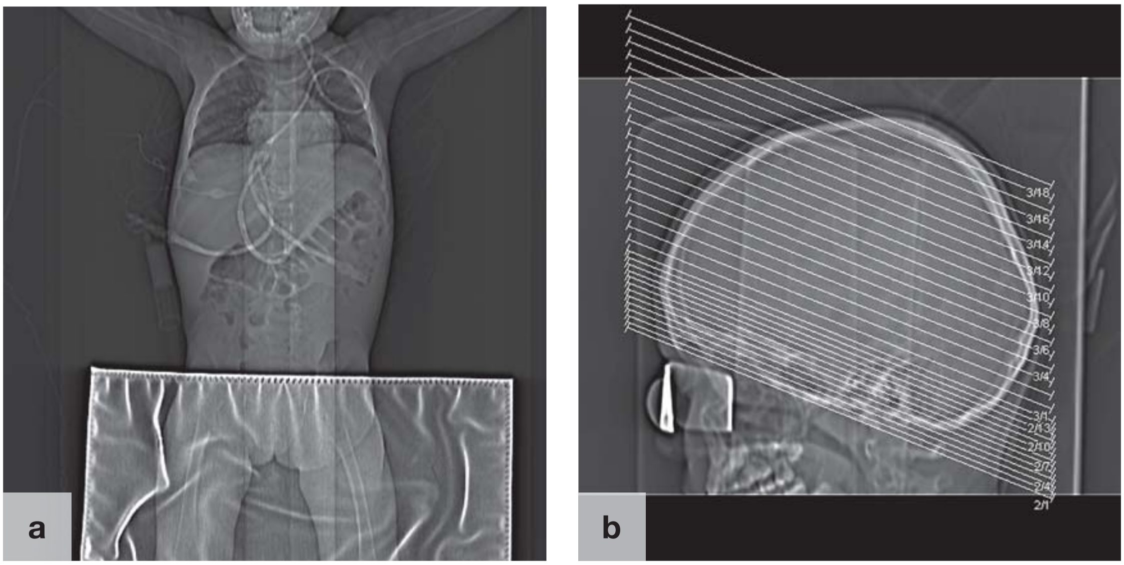


Figure 4: Radiation protection in computed tomography

a) Inappropriately long topogram before a chest CT, with unnecessary exposure of additional parts of the body.

b) Slicing of a cranial CT parallel to the base of the cranium to protect the orbits. The topogram also shows a layer of lead rubber covering the lenses (authors' images, UKGM, Giessen).

department CT scans account for 2% to 4% of all examinations).

The complexity of age- and indication-dependent machine adjustment in pediatric radiology requires compulsory general examination strategies in the form of operating procedures (OPs), guidelines and dose limits (9, 22–25). As there can be huge variations in the dose of radiation involved in X-ray examinations of the same organ, depending on the X-ray technique used, the Society for Pediatric Radiology (GPR, Gesellschaft für Pädiatrische Radiologie) has introduced a system of X-ray cards for children. Alongside the standard documents on performed examinations, X-ray cards also make it possible to state the applied dose of radiation. This may make it possible to raise awareness of the risk.

The current fall in pediatric radiology facilities, not only those in universities, together with the lack of well-trained physicians prepared to specialize in the less lucrative field of pediatric radiology, may result in a decrease in professional expertise, a situation in which children will suffer.

Conflict of interest statement

Prof. Alzen holds a patent for a device to fill animals' hollow organs with biocompatible gas. Prof. Benz-Bohm declares that she has no conflict of interests.

Manuscript received on 31 March 2010, revised version accepted on 15 March 2010.

Translated from the original German by Caroline Devitt, MA.

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eTABLE

Technical developments of computed tomography and their effects on examination-associated radiation doses (e9, e11, e14, e15)

Year introduced	Name	Description of technical innovation	Dose reduction
1994	CARE Dose 4D	Fully automatic, real-time dose modulation according to the absorption values measured within the body	20 to 68%
1997	UFC detectors	Ultra-fast ceramic detectors with a gadolinium oxysulfide scintillator. The introduction of these detectors laid the essential foundations for subsequent multidetector technology and dual-source CT.	Up to 30%
1999	Adaptive ECG synchronization	During a heart CT there is pulsed tube radiation only during the phase of the heart cycle selected beforehand. During the rest of the heart cycle, which is of no use in image reconstruction, no radiation is applied.	30% to 50% in heart CTs
1999	HandCARE	If the examiner's hand is inside the gantry when a CT is performed, radiation in this area can be switched off. This means that only the part of the hand that overlaps with the patient's body, and is partly protected by it, is exposed to radiation.	70% for the examiner
2002	80 kV pediatric protocols	When small areas are examined, reducing the tube voltage substantially reduces the dose when compared to conventional X-rays. The standard tube voltage for adults, up to 130 kV, is not necessary when scanning children's smaller bodies. If examinations are performed on high-contrast areas such as the lungs or bones, the tube voltage can be further reduced by a fraction of the standard values (low-dose CT).	Up to 50%
2005	Dual-source CT	Two tubes set at a 45° angle rotate simultaneously in the gantry. This allows a dose-efficient, shorter scan time together with adaptive ECG triggering and automatic adjustment of table movement to heart rate.	Up to 50% when compared to single-source scanners
2007	Adaptive cardio sequence	Prospective ECG triggering (the step and shoot technique) reduces the average radiation dose in CT coronary angiography to approx. 2.5 mSv.	1 to 3 mSv of dose in CT coronary angiography
2007	Adaptive dose shield	An asymmetrical collimator shield prevents overranging/overscanning of parts of the body not included in the examination at the beginning and end of a spiral CT. Depending on the total length of the body examined, the dose can fall by between 5% and 20%.	Up to 25%
2008	Flash spiral	Two rows of detectors are used simultaneously, allowing the table feed to be increased to 45 cm/s. The main use of this is in imaging of the coronary vessels.	<1 mSv of dose in heart CT
2008	Selective photon shield		No increase in dose
2008	4D noise reduction		Up to 50%
2008	X-Care	Using organ-specific dose modulation, direct exposure of particularly radiosensitive organs such as the thyroid, breast or lenses can be avoided (similar to HandCARE).	Up to 40%
2009	Iterative Reconstruction in Image Space (IRIS)	Special image processing in which a master image is first reconstructed on the basis of raw data and then gradually further reconstructed using iterative image correction. The result is an artifact- and noise-reduced image.	Up to 60%