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Diagnostic imaging in children

Recommendation of the German Commission on Radiological Protection

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Preface

In the past decade, there have been considerable technical advances in imaging procedures. Modern digital radiographic procedures, hybrid technologies such as PET-CT, PET-MRI and SPECT-CT and in particular multi-detector computed tomography with new detector and image reconstruction technologies are being used increasingly in diagnostic procedures. For diagnostic investigations with imaging procedures in children and adolescents, this has resulted in relevant changes with respect to the justifying indication and the technical implementation of radiographic procedures, with special attention to radiation protection.

In view of the numerous new and further developments in methodology and device technology since publication of the recommendation ‘Diagnostic imaging of children, radiation protection, justification and efficiency’ (‘Bildgebende Diagnostik beim Kind – Strahlenschutz, Rechtfertigung und Effektivität’) of the German Commission on Radiological Protection (SSK) in the year 2006, it has become necessary to update the recommendations given in that publication to reflect the current state of scientific knowledge. Furthermore, the recommendation was to be expanded to the field of nuclear medicine.

This necessary update of the 2006 recommendation was prepared by the following members of a working group formed by the ‘Radiological protection in medicine’ committee of the SSK specialising in paediatric radiology, nuclear medicine and medical physics:

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1 Introduction

Article 61 (1) Letter a of Council Directive 2013/59/Euratom of 5 December 2013 laying down basic safety standards for protection against the dangers arising from exposure to ionising radiation (Euratom 2013) stipulates that Member States shall “ensure that appropriate medical radiological equipment, practical techniques and ancillary equipment is used in medical exposure of children”.

This requirement was implemented in Section 86 of the German Radiation Protection Act (StrlSchG 2017) by way of “Empowerments to issue ordinances for the protection of persons in the case of the use of ionising radiation or radioactive substances on people” and in the “Ordinance on the further modernisation of radiation protection legislation” (StrlSchV 2018) as follows:

“The radiation protection executive shall ensure that, in the use of ionising radiation or radioactive substances on persons under 18 years of age, appropriate procedures as well as equipment, devices and instruments are available and are used in order to do justice to the particular sensitivity of such persons to ionising radiation.” (Section 120 (3) StrlSchV).

When it comes to the use of ionising radiation on persons, the justification, observance of limits and reference levels and the optimisation of radiation exposure are paramount in radiation protection legislation. Section 83 (3) StrlSchG stipulates that ionising radiation and radioactive substances may only be used in medical practice after a medical doctor who possesses the requisite specialist knowledge in radiation protection has established an individual justifying indication. Diagnostic procedures that do not involve exposure to ionising radiation, such as ultrasound or magnetic resonance imaging, must be given adequate consideration as alternative procedures and should preferably be used in children and adolescents, provided they achieve the same level of diagnostic accuracy.

According to Section 83 (5) StrlSchG, the exposure resulting from an application shall be limited to the extent that this is compatible with the possibilities of medical technology. The image quality and thus also the radiation dose should be dictated by the medical question; this means that any and every attempt to minimise the dose must also take the required image quality into account.

These principles must be applied all the more strictly when using ionising radiation and radioactive substances in children due to their increased sensitivity to radiation. Unlike in the SSK recommendation ‘Recommendations for medical imaging procedures’, which was updated in 2019 and recommends the most appropriate imaging procedure for various clinical questions with a particular view to radiation protection, the recommendation ‘Diagnostic imaging of children, radiation protection, justification and efficiency’ published by the SSK in 2006 focused on optimising radiation protection through the application and use of appropriate device technology and imaging techniques.

In an advisory mandate of 19 July 2017, the Federal Ministry for the Environment, Nature Conservation, Buildings and Nuclear Safety (BMUB) wrote:

“In the past decade, there have been considerable technical advances in imaging procedures. Modern digital radiographic procedures, hybrid technologies such as PET-CT / PET-MRI and in particular multi-detector computed tomography with automatic exposure control are being used increasingly in diagnostic procedures. For diagnostic investigations with imaging procedures in children and adolescents, this has also resulted in relevant changes with respect to the justifying indication and the technical implementation of radiographic procedures, with special attention to radiation protection.“

On these grounds, the SSK was asked to update the 2006 recommendation to reflect the current state of scientific knowledge.

2 Recommendations

The SSK stresses the importance of the justifying indication as the key foundation for radiation protection in the use of ionising radiation in children and adolescents. Beyond the requisite specialist knowledge in radiation protection, the use of ionising radiation in children should be entrusted to physicians who are trained in paediatric radiology and/or in paediatric nuclear medicine imaging. An examination technique and environment that is appropriate for investigations in children is required as well as technical radiology assistants who are trained in dealing with children. Within the scope of diagnostic imaging – particularly in children – the StrlSchV stipulates that preference should be given to procedures that do not involve the use of ionising radiation (ultrasound and magnetic resonance imaging (MRI)).

All efforts to lower radiation exposure should be exhausted. Therefore, the SSK recommends the following:

– Ultrasound should constitute the basic examination in diagnostic imaging during childhood[1]. In keeping with ionising procedures, the ALARA principle should be applied (Kollmann et al. 2020), especially in newborns and infants or within the scope of special applications (e.g. contrast-enhanced ultrasound, elastography).

– Except for acute severe traumatic brain injuries or polytrauma, and provided the diagnostic accuracy is better than or equal to that of computed tomography (CT), preference should be given to magnetic resonance imaging (MRI) as a further diagnostic procedure. In small children, in whom sedation is frequently required, the greater risk of sedation or anaesthesia during MRI should be considered when establishing an indication for MRI.

– Appropriate technical equipment should be available when performing radiographic investigations in children (switching time, voltage, filtering). Dose reduction should always take account of the indication and the clinical question. In paediatric applications, detectors with a high DQE should be used. Optimised collimation is mandatory and constitutes one of the major elements of radiation protection. When using patient contact shielding, dose-increasing effects should be avoided. Particularly during examinations involving high radiation doses (e.g. radiography of the abdomen, pelvis, spine) alternative procedures – which provide at least the same level of accuracy – should preferably be used.

– Fluoroscopy investigations in children should be carried out with devices featuring pulsed fluoroscopy, a removable grid and additional filtering. For systems that are not equipped with a digital, dose-neutral zoom function, examinations should be performed with the lowest possible zoom factor. Strict collimation settings that take account of the clinical question should be used. Documentation should preferably be done using the stored digital image (Last Image Hold), which usually provides sufficient information for diagnosis. The dose area product and the fluoroscopy time should be documented. When verifying the indication for a fluoroscopy investigation, preference should be given to alternative procedures that offer the same level of accuracy (e.g. voiding urosonography instead of voiding cystourethrography).

[1] For ultrasound applications in humans see also SSK 2012.

- In computed tomography, any dose reductions should take account of the clinical question; this may include a decrease in the effective tube current time product (mAs) and the voltage (kV). For CT scans in children, appropriate examination protocols should be available and applied. Medical doctors and technical radiology assistants should be required to attend special further training with a view to the rapid advances in dose reduction in CT, enabling them to apply dose optimisation procedures with the necessary expertise (including iterative reconstruction, possibly also artificial intelligence). The current diagnostic reference levels have to be strictly adhered.
- For nuclear medicine investigations, the focus should lie on decreasing the amount of activity of a radiopharmaceutical administered based on a child's weight relative to adults.
- When using PET-CT, the need for a diagnostic CT component should be reviewed on an individual basis.
- If available, PET-MRI should be given preference over PET-CT.

3 Characteristics of diagnostic exposure during childhood

3.1 Biological characteristics

3.1.1 Increased sensitivity to radiation

The higher cell division rates of the growing body, among other things, make children particularly sensitive to radiation. The effect of moderate doses of ionising radiation on the development and maturation of the organ systems (e.g. cognitive function) is the subject of research and discussion (Pasqual et al. 2020). Dose-related damage in children has been reported (e.g. eye lens, heart, brain; (Chu et al. 2020)). In comparison with adults, children also have a longer remaining life expectancy and therefore a higher lifetime risk of radiation-induced cancer. Following exposure during childhood, the risk for many malignant diseases remains increased throughout their life (Linet et al. 2012). Follow-up studies among children with a history of irradiation for the treatment of benign diseases such as haemangioma and tinea capitis, as well as the Life Span Study of atomic bomb survivors showed that the most radiosensitive organs in children are the thyroid gland, breasts, bone marrow, brain, and skin (Kleinerman 2006, UNSCEAR 2013). On an international level, these insights led to recommendations and measures to reduce exposure to medical radiation (Goodman et al. 2019).

The medical care of very small preterm babies can also require the diagnostic use of ionising radiation. In such cases, this involves exposure of cells that are actually still foetal cells. Even though the risk of malformations and misdevelopments in the foetal period is thought to be lower than during embryonic development (organ formation period), it will only be possible to assess the relevance of the stochastic effect for these very immature children after some decades (Tomà et al. 2019). In the 1950s, the Oxford Study of Childhood Cancers (OSCC) estimated that the risk of childhood cancer was twice as high in children who had been exposed to radiographic imaging of the maternal pelvis during pregnancy (Giles et al. 1956). A meta-analysis of more recent data was not able to demonstrate a statistically significant risk increase (Abalo et al. 2021).

3.1.2 Body size and anatomy

Given the wide range in physical sizes between preterm babies and adolescents, it is not possible to specify technical parameters for radiographic investigations and general diagnostic reference levels (DRL) for children; instead, DRLs must take account of the respective body weight and the sagittal diameter. The younger a child or the smaller its body size, the more its anatomy differs from that of an adult. Radiosensitive organs in children with a small body size, for example, are much closer to an exposed field than in adults (e.g. thyroid and ovaries in chest radiographs) and, if collimation settings are insufficient, they are also exposed to radiation. In preterm babies, additionally opening the aperture by as little as 1 cm causes an already significant increase in field size and thus in total exposure (Schneider und Seidenbusch 2019). It should also be considered that small children have a higher relative amount of (radiosensitive) red bone marrow in the extremities and skull, all of which are unnecessarily exposed if collimation settings are insufficient or if the scan length is not restricted in the CT.

3.1.3 Genetic risk

Children are potential future parents, which means that the genetic effects of ionising radiation on the gonads during childhood must be considered with a view to its effects in adulthood. Epidemiological findings so far suggest that there is no evidence of a connection between radiation exposure and the occurrence of genetic damage in humans (Boice et al. 2003, Nielsen et al. 2018).

3.2 Risk for radiation damage

One important factor that influences the risk of radiation is the age at which exposure takes place. According to ICRP Publications 103, 121 and 147 (ICRP 2007, ICRP 2013, 2021), children who were exposed to radiation for diagnostic purposes have an increased excess lifetime risk for cancer compared with individuals who were exposed during adulthood. According to UNSCEAR the lifetime risks are 2 to 3 times higher (UNSCEAR 2013). The effect is all the more serious the younger the child is. Consequently, the indication for the use of ionising radiation must be reviewed even more strictly, especially in newborns, infants and young children.

Stochastic effects of radiation are defined as effects with a probability of occurrence that increases with the dose. In line with the linear no-threshold model (LNT model) applied in radiation protection, it is assumed that the risk – with no threshold – is also proportionally increased at low doses. In the LNT model, the severity of the resulting disease is independent of the dose. However, radiobiological effects of low doses are presumably more complex than assumed with this simple LNT model. Even if the absolute figures are low, retrospective studies have shown evidence of an increased lifetime cancer risk following diagnostic CT scans during childhood (e.g. Mathews et al. 2013, Pearce et al. 2012, Meulepas et al. 2019). Possible shortcomings with regard to distortions (bias) and insufficiently differentiated data are discussed for the cited studies (Walsh et al. 2014). The results of the extensive multi-centre European EPI-CT study[2] assessing the risk of cancer in connection with CT scans following a longer follow-up period may paint a clearer picture (Bernier et al. 2019). The literature on the risk of radiation from conventional projection radiography is ambiguous (Abalo et al. 2021, Goodman et al. 2019).

At current levels of knowledge, radiation-induced leukaemia and solid tumours (for example in the thyroid, brain, breast and intestine) occur with a latency period. Generally, the latency period for leukaemia is at least two to five years, for solid tumours at least 10 to 15 years (Linet et al. 2012, Kleinerman 2006, Goodman et al. 2019). Radiation-induced leukaemia and solid tumours can still occur even decades after exposure. For malignant tumors that typically occur in adulthood, for example breast cancer, a radiation-induced increase in cancer rates following exposure at a young age is generally observed at a higher age. Therefore, only very large

[2] https://epi-ct.iarc.fr/

epidemiological studies with a longer follow-up period will allow us to draw sufficiently accurate conclusions on the risk of radiation after a relatively low exposure in younger years.

3.3 Characteristics of examinations in children

In all efforts for dose reduction there should be no compromise on image quality, because any diagnostically unusable radiographic image or CT scan constitutes preventable exposure. Not only the administered dose, the hardware and the post-processing by the software, but also the positioning of the patient and the resulting projection must be adequate to ensure an accurate diagnosis. Appropriate handling of children requires trained and dedicated radiography assistants. While an empathetic approach and flexibility is very important when dealing with sick children, excessive caution must not be allowed to lead to faulty projections, as these also constitute unnecessary exposure. For example, in small children who are unable to cooperate, chest radiographs should still preferably be taken during inspiration and injured extremities x-rayed in orthograde projection.

Particularities of radiographic settings and CT parameters for paediatric imaging have been published (Becht et al. 2019, Sorantin 2013) and are an absolute prerequisite for an adequate diagnosis. Young children must be safely immobilised for the respective examination in order to prevent faulty projections and motion artifacts. An adequate selection of appropriate aids (foam cushion wedges, sandbags, radiation resistant gloves) as well as patient contact shielding (e.g. gonad protection) (SSK 2022) must be available (BMU 2009) and used in accordance with the recommendation ‘Use of patient contact shielding in the diagnostic application of X-rays in humans’ (SSK 2022). The staff should be adequately and comprehensibly instructed and attend regular training (Lenzen et al. 2021).

For longer-lasting investigations (e.g. fluoroscopy), child-friendly furnishings as well as audio or video devices should not only provide a pleasant environment but also contribute specifically towards ensuring a successful examination with the shortest possible fluoroscopy duration.

As a general rule, in all examinations radiation exposure should be reduced as far as possible through correct collimation, appropriate parameter settings and positioning. This applies to all examinations involving ionising radiation, such as radiographic imaging, fluoroscopy, digital volume tomography and CT, as well as to nuclear medicine investigations.

Owing to the lack of cooperativeness in young children, sedation or anaesthesia are frequently required to obtain reliable results. Particularly in children who require sedation for immobilisation, the greater risk of sedation should be considered in the indication.

4 Procedures without ionising radiation

Due to possible adverse effects, prior to using ionising radiation in childhood and adolescence alternative investigation methods must be considered when establishing the justifying indication and preference given to any such methods, provided they are appropriate for answering the clinical question. Along with comprehensive knowledge about physical-technical possibilities and limitations of the various methods, decision making also requires a wealth of experience in the physiology, development and pathology in childhood and adolescence – from exceedingly preterm babies weighing 300 g to adolescents weighing 150 kg. Besides reducing radiation exposure through time savings, the use of ultrasound and magnetic resonance imaging in accordance with the indication instead of stepwise diagnostics is also associated with economic benefits.

4.1 Ultrasound

In children and adolescents, ultrasound constitutes the basic examination in diagnostic imaging and, owing to innovative technical developments in transducers, hardware, computer technology and application software, is frequently the only imaging procedure needed for diagnosis (Hwang et al. 2019). All organ systems can now be imaged by ultrasound. This method not only offers the advantage of completely dispensing with radiation exposure, it also boasts widespread availability and a high mobility of the investigation, with the option of examining subjects inside an incubator or at the bedside. Innovations in ultrasound, such as elastography and contrast-enhanced ultrasound, have allowed some examination methods that involve ionising radiation to be replaced. In vesicoureteral reflux diagnosis, for example, contrast-enhanced voiding urosonography (VUS) has become a valid alternative to voiding cystourethrogram (VCUG) which involves x-radiation (Waginger und Mentzel 2020). Ultrasound elastography of the liver takes precedence over an invasive biopsy in the event of diffuse liver changes (fibrosis) in childhood. In the setting of acute ileocolic intussusception, ultrasound-assisted disinvagination with a liquid enema is preferable to a contrast enema.

When using ultrasound, consideration must be given to mechanical (compression and straining of tissue (cavitation), pressure increase in cells), thermal (energy absorption, heating) and chemical (dissociation of water molecules at outputs of 3 W cm^{-2}) effects. While therapeutic ultrasound is potentially dangerous due to a high energy input with possible tissue destruction, this is not expected to occur during diagnostic ultrasound and has not been demonstrated thus far. Nevertheless, it should be noted that the output and duration of ultrasound must be minimised, especially in preterm babies, newborns and seriously ill children. Doppler procedures should therefore be used with the lowest possible output and for the shortest possible duration. The ALARA principle should also be applied in cranial ultrasound examinations of newborns (Lalzad et al. 2017) and in foetal ultrasound (SSK 2012) (Cibull et al. 2013, Kollmann et al. 2020). The use of ultrasound contrast agents in combination with Doppler procedures bears a higher risk of cavitation owing to oscillations and bursting of microbubbles. No restrictions apply to standard ultrasound examinations performed in the brightness mode, provided quality standards and safety precautions are observed (e.g. ultrasound of the eyeball and orbit using only special transducers and default settings with a reduced mechanical index). Corresponding standards stipulate limiting the energy to an ultrasonic intensity of 50 mW cm^{-2} for the eye and 720 mW cm^{-2} for the other applications (DIN EN 60601-2-37).

The SSK recommends the following:

Ultrasound should constitute the basic examination in diagnostic imaging during childhood[1]. In keeping with ionising procedures, the ALARA principle should be applied (Kollmann et al. 2020), especially in the case of newborns and infants and within the scope of special applications (e.g. contrast-enhanced ultrasound, elastography).

4.2 MRI

Except for emergency diagnostics in the event of multiple trauma, special clinical questions involving the musculoskeletal apparatus and the lungs, MRI has become the preferred method for extended diagnostic imaging in children compared to CT, complemented by hybrid procedures in paediatric oncology. Diffusion- and susceptibility-weighted imaging, spectroscopy, dynamic contrast-enhanced studies, vascular and perfusion imaging without the use of contrast agents, as well as the possibility of whole-body imaging and the reduction of respiratory and motion artefacts by means of modern acquisition and trigger modes, represent MRI innovations that have led to a high level of acceptance of magnetic resonance imaging in children and adolescents. Today, whole-body MRI is considered an alternative to bone scintigraphy and, if indicated, functional MR urography as an alternative to MAG3 scintigraphy (Kirsch und Mentzel 2018, Zadig et al. 2021).

The large number of investigations and the widespread availability of devices with static magnetic fields of 1.5 T or 3.0 T, along with shorter examination times, lead to cost savings and greater economic efficiency in paediatric radiology. In children who are unable to cooperate, sedation or anaesthesia are frequently required to obtain reliable results. Sedation is generally possible in MRI investigations that require a limited examination time. Lack of compliance requires the use of anaesthesia during MRI when long protocols (e.g. whole-body MRI in children for cancer staging) or examinations involving breath-hold techniques (e.g. abdominal MRI) are indicated. This must be taken into consideration and clarified when establishing the indication, and prior to scheduling the examination.

Besides the confined space of the examination tube and the relatively long scanning time, the high noise level in particular during the examination is stressful for children. All efforts to ensure the highest patient safety must focus primarily on preventing possible harm to children through the use of non-ionising radiation in MRI and on facilitating the examination with appropriate medications and MRI contrast agents (Holland et al. 2014). This applies likewise to unborn children within the scope of foetal MRI (Zvi et al. 2020).

Besides the technical hazard potential posed by metal objects, electronic implants and stray fields, possible biological effects of static magnetic fields of the strongest magnet (B_0) in particular must be taken into account when using MRI, even though a reproducible harmful effect of diagnostic imaging at field strengths of 0.2 T to 3.0 T has not been demonstrated (ACR 2020).

Time-varying magnetic gradient fields can induce currents in the biological organism, the intensity of which depends on the conductivity of the tissue, the radius of the conductive loop and the rate of change of the gradient fields. There is, for example, an increased risk for skin burn injuries due to direct skin-to-skin contact points and loop formations, which must absolutely be considered when positioning the patient. Additional factors include the spatial orientation of the gradients to the tissue, the diameter of the scanned object, as well as the frequency and duration of induction. In diagnostic MRI, the resulting increase in temperature is negligible, provided the respective limits (current density $30\,\mu A\,cm^{-2}$ at $30\,T\,s^{-1}$) are observed. Observing threshold values prevents possible neuromuscular stimulation, cerebral seizures, arrhythmias and the occurrence of phosphenes.

Pulsed high-frequency fields (the classic proton resonance is 42 MHz per Tesla) are designed to measure tissue densities; at the same time, they increase the temperature of the tissue. Threshold values for the high-frequency energy absorbed by the body (specific absorption rate, SAR, relative to body weight) are specified for MRI scans of different body regions, thus precluding clinically relevant temperature increases. However, further development of MRI sequences can also lead to an increased energy input and thus a higher SAR; this must be considered by the (paediatric) radiologist particularly when examining preterm and full-term babies as well as infants and intensive care patients and also during foetal MRI (ACR-SPR 2020, Salerno et al. 2018).

The SSK recommends the following:

Except in the case of acute severe traumatic brain injuries or polytrauma, and provided the diagnostic accuracy is better than or equal to that of computed tomography (CT), magnetic resonance imaging should be given preference as a further imaging procedure.

In small children, in whom sedation is frequently required, the greater risk of sedation during MRI should be considered when establishing an indication for MRI.

5 Optimising radiation protection during ionising radiation

5.1 Projection radiography

5.1.1 Aspects relating to device technology

Concerning the quality requirements governing the use of projection radiography, please refer to the current guidelines of the German Medical Association (BÄK). Regarding the indication for radiography, for various indications there has been a shift towards methods that do not involve ionising radiation. For dose-relevant examinations in particular (e.g. abdomen, pelvis, spine), alternative methods must be pursued (e.g. ultrasound). Today, there are barely any indications for radiographic imaging of the skull (e.g. suspected non-accidental head injury). Constant advancements in technology have resulted in a shift away from analogue technologies towards digital detector technologies, with all its advantages, in paediatric radiology and especially also in radiographic examinations of extremely premature babies (<1000 g). The high heart rates and uncontrolled body movements, particularly in younger children, require very short exposure times in diagnostic radiography in order to prevent motion artefacts. Therefore, the aim is to always use devices that allow switching times of less than 5 ms. Every increase in absorption by materials located behind the patient leads to an increase in radiation exposure. This means that grids should be easily removable and that table tops and table pads should be optimised as far as possible. Particularly when imaging small objects, the table pad should be removed due to the unnecessary absorption and a short object-to-detector distance ensured. Therefore, for imaging in a supine position, the folded vertical bucky stand should preferably be used, or better yet, the child should be positioned directly on the detector. If anti-scatter grids are recommended, a virtual grid should be used where possible. Virtual grids minimize the contrast-reducing influence of scattered radiation without increasing radiation exposure. If such grids are not available, the grid should be equipped with an adequate image improvement factor Q and a high primary radiation transmission T_P according to DIN EN 60627.

5.1.2 Imaging technique (filtering, tube voltage, grids)

As mentioned above, the imaging technique in children is not uniform. Technique depends strongly on the child’s constitution and the clinical question.

Therefore, the *tube voltage and pre-filtering* should be dictated by the thickness of the body region being exposed and the required contrast-to-noise ratio. A significant reduction in the skin dose through the use of high tube voltages and pre-filtering is achieved only for objects with a thickness that exceeds 10 cm. The impact of these measures on radiation exposure becomes lower as the diameter of the object decreases. The tube voltage should not be below 60 kV when imaging the trunk and not below 55 kV in preterm babies. In particular when imaging distal sections of the extremities, lower tube voltages and filter combinations that decrease hardening of the X-ray beam can improve the contrast-to-noise ratio (Hess und Neitzel 2012, Knight 2014).

Filters that are additionally applied during paediatric imaging are generally 1 mm Al and 0.1 mm to 0.2 mm Cu. These filters serve to lower the skin dose by 30 % to 40 %. Filters act mainly on lower radiation energies and do not modify the maximum energy. The tube voltage, on the other hand, acts on the entire spectrum of radiation. For radiation protection purposes, a high filter value should be used; the tube voltage should be reduced slightly in order to optimise the image quality. Details relating to the imaging parameters can be found, among others, in the guidelines of the German Medical Association (BÄK) on quality assurance of X-ray examinations (BÄK 2022).

Use of a *grid* only becomes necessary when imaging older children around the age of ten years, or for objects with a sagittal diameter that exceeds 15 cm. The child's age only correlates poorly with the level of scattered radiation. Performing an examination without a grid corresponds to a dose reduction by a factor of 2 or 3 (at higher levels of scattered radiation also by a factor of three to four).

Optimal collimation is essential for radiation protection. For the adjacent organ regions, correct collimation can eliminate the strong primary beam. In addition, the collimation should also decrease the detector or grid area hit by the primary beam, as this causes a high level of scattered radiation. In this regard, it must be noted that the dose area product increases with the field size. The entrance surface dose, however, only changes minimally.

The use of automatic exposure is frequently not possible in children due to their small body size. The effectiveness of manual settings depends on the staff's experience. In contrast to underexposure, any overexposure in a digital image resulting from lack of experience in device settings cannot be easily seen by a change in image quality. Here, the only marker is the dose indicator. It correlates with the image detector dose and indicates whether the intended dose was reached or exceeded on the detector during exposure. Documentation of the dose indicator values and an evaluation of every exposure are stipulated by law (Section 85 (1) No. 3 StrlSchG). The dose indicator should be displayed not only on the actual device but also on the workstation in order to enable a four-eyes principle by the technical staff and the medical personnel.

The function of the dose indicator should furthermore constitute a mandatory element of radiation protection training and be included in the guidelines on image quality. However, the sheer number of proprietary indicators of individual manufacturers on older devices is currently preventing widespread use.

Radiation exposure of the mammary gland, especially in girls, should be avoided or minimised as far as possible. For this reason, posterior-anterior (PA) imaging should preferably be used in thoracic examinations. For radiographic imaging of preterm and term born babies in the incubator, use of the slide-out tray in the incubator should be avoided where possible and the detector placed directly under the child due to the increased absorption in the positioning mat and base plate. Depending on the child's clinical condition, radiographic imaging of the thorax can also be performed with the infant in the BABIX holder on the vertical bucky stand (Schneider und Seidenbusch 2019).

5.1.3 Image detection with digital phosphor storage plates and flat-panel detectors

Digital detectors are characterised by very high dynamics, which means that they can be used within a wide dose range. However, low detector doses result in a decreased signal-to-noise ratio. For objects with a high contrast – for example, air/soft tissue or bone/soft tissue – this may be acceptable to a certain extent. Here, an internal optimisation process should be implemented to achieve the optimal image quality.

Flat-panel detectors generally have a markedly increased quantum yield (DQE), which provides an adequate image quality even at low detector doses. This does not always apply to digital image plate radiography. The dose requirement may even be higher than when using a film-plate combination. Notwithstanding, the advantage of storage plate systems is their lower incorrect exposure rate as well as their ability to process and archive digital images. Owing to the lower DQE and the markedly increased risk of incorrect exposure, the use of film/plate systems should be avoided in paediatric radiology.

Concerning flat-panel detectors in paediatric examinations, technologies with the highest DQE (e.g. with caesium iodide instead of gadolinium oxysulfide scintillators) should be used.

The maximum sensitivity of all detectors (including storage plates and intensifying screens) is strongly dependent on energy. This means that the maximum sensitivity of the detector is only guaranteed within a defined energy band. Therefore, when switching a radiography machine to a different detector, the automatic exposure, exposure tables and the radiation qualities used must be adapted to the parameters of the respective detector and the examination protocols must be revised accordingly. Only in this way can these detectors be used to their full potential.

For the peripheral skeleton the image detector dose should be below 5 µGy and for the trunk below 2.5 µGy (BÄK 2022). Detectors with the highest possible sensitivity should be used. The dose can be further reduced for clinical questions relating to foreign bodies, ileus or shunts in abdominal scout views. The same applies for full-length imaging of the spine and leg (full leg and full spine). Here, the target is an image detector dose below 1.25 µGy.

5.1.4 Patient contact shielding

According to recent studies, the benefit of patient contact shielding has not been clearly established for all organ systems, so that it may be omitted under certain conditions (AAPM 2019, Frantzen et al. 2012, Hiles et al. 2021, Jeukens et al. 2020, Kaplan et al. 2018, Marsh und Silosky 2019, SSK 2022, Yu et al. 2019). At any rate, the dose-increasing effect of patient contact shielding placed between the radiation source and the exposure chamber should be avoided when automatic exposure control is used (Kaplan et al. 2018, Culp et al. 2014,Frantzen et al. 2012).

The SSK recommends the following:

Appropriate technical equipment should be available when performing radiographic examinations in children (switching time, voltage, filtering).

Dose reductions should always take account of the indication and the clinical question.

In paediatric settings, detectors with a high DQE should be used.

Optimised collimation is mandatory and constitutes one of the major elements of radiation protection.

When using patient contact shielding, dose-increasing effects should be avoided.

Particularly during examinations involving high radiation doses (e.g. radiography of the abdomen, pelvis, spine) alternative procedures – which provide at least the same level of accuracy – should preferably be used.

5.2 Fluoroscopy

5.2.1 Aspects relating to device technology

For fluoroscopy examinations, devices that feature different projection directions of the emitter are available. The orientation of over-couch (AP projection) or under-couch (PA projection) devices is rigid, while the projection direction of C-arm devices can be adjusted.

Scattering of radiation from the body of the patient is the primary source of radiation exposure of the examiner. Due to the backscatter, the maximum exposure occurs on the entrance side of the radiation. This must be borne in mind, especially when using over-couch devices. However, the amount of backscatter decreases with small fields and small object diameters. As the maximum exposure for patients likewise occurs on the entrance side, this should be taken into account when positioning the patient (e.g. by using the prone position), if possible. In this case, too, the effect decreases as object diameters become smaller.

The disadvantages of over-couch systems thus only become relevant as children get older. In young children up to the age of around twelve years, over-couch devices provide better accessibility and also have the advantage of lowering radiation through the use of a light-beam localiser. In adolescents or in children within an adolescent weight range, under-couch devices are preferable.

In paediatric radiology, the lowest possible frequency should be used in fluoroscopy examinations involving pulsed fluoroscopy, such as VCUG, as this enables an up to 90% reduction in exposure (Ward et al. 2008). At fluoroscopy workstations that are used for examining paediatric patients, it must always be possible to remove the anti-scatter grid, as this grid leads to a markedly higher exposure in infants and young children. As the lower volumes within the field of radiation only cause a small amount of scattered radiation, grids do not significantly improve the image contrast.

One effective way to lower the exposure during fluoroscopy examinations is to use the 'Last Image Hold' and 'Last Image Run' feature; when activated, the last fluoroscopy image or the last fluoroscopy sequence is always displayed on the monitor. Using the stored fluoroscopy image or sequence, images of sufficient quality can frequently be stored for documentation purposes. Newer systems also provide the option of averaging multiple images ('Snap Shot') during permanent sequence recording. This feature uses the images from the fluoroscopy series to create individual images with considerably less noise without actually having to create an individual image, which would entail greater exposure.

Besides collimation using the Last Image Hold (LIH) and Last Image Run (LIR) features, an ideal paediatric fluoroscopy workstation features automatic positioning from the Last Image Hold as well as age- or weight-dependent examination protocols with special exposure-lowering characteristics for automatic exposure control (AEC) of the fluoroscopy.

Table pads should be removed for AP imaging or exhibit only minimal absorption. The patient-to-detector distance (ODD) should be minimal and the focus-to-object distance (FOD) maximal.

The detector format (zoom) influences the spatial resolution, the dose rate and the absorbed dose. The zoom function should be used only to improve the spatial resolution and not to enlarge the image. This applies equally for analog image intensifiers and digital flat-panel detectors.

Additional filters in the beam path should be used to absorb the low-energy proportion of the X-ray radiation and thereby lower the incident dose. The effect decreases as object diameters become smaller. The image contrast, on the other hand, also decreases with increasing filter thickness. Similar effects occur at higher acceleration voltages. The aim here is to find the optimal balance between radiation exposure and image quality for each age or weight category and to record it in the examination protocol.

For examinations involving iodinated contrast media, the radiation energy should be adjusted to the K-absorption edge (33 keV) in order to maximise the contrast.

When examining the trunk, the dose area product must be documented, along with the fluoroscopy time and, if available, the air kerma. Details of the entire examination procedure, including all dose values and device settings as well as the incident angles and field sizes of each individual irradiation event should be transmitted to the picture archiving and communication system (PACS) and the dose management system (DMS) via a DICOM Dose Report protocol and made available there for further evaluation.

Section 114 StrlSchV stipulates that the fluoroscopy devices are required to have a function that electronically records the exposure parameters and is electronically usable for quality assurance. A transitional period until 2023 applies for this.

5.2.2 Diagnostics (VCUG, SBFT, colon CE)

Even though a range of alternative procedures is available, functional fluoroscopy investigations continue to be the standard examination in the diagnostic work-up of children. This essentially stems from the fact that the procedures can be carried out quickly, are safe and can generally be performed without sedation. In the light of more recent evidence regarding the risk of sedation, this is particularly relevant in young children up to the age of seven years (Backeljauw et al. 2015). A series of innovative methods that do not require the use of ionising radiation for functional examinations of the gastrointestinal tract or the genitourinary system (e.g. contrast-enhanced ultrasound) has been developed and tested in the last years. They must be given due consideration as an alternative when establishing an indication, but generally require a sophisticated technique and experience of the examiner.

When using ionising radiation, the following principles (bearing in mind the ALARA principle) must be complied with:

- The findings of all relevant previous examinations, including alternative methods (endoscopy, ultrasound, MRI etc.) should be available and known, both for establishing the justifying indication and for planning an examination on the basis of the clinical question. This helps prevent incorrect indications but also decreases fluoroscopy times significantly (5.2.1).
- Critical consideration of the use of patient contact shielding (5.1.4).
- Use of modern device technology (5.2.1).
- Use of collimation to lower exposure, e.g. by means of a light-beam localiser (5.2.1).
- Use of additional filtering (5.2.1).
- Low-dose examinations with an exposure that is both reduced and adapted to the clinical question, including the lowest possible pulse frequency (up to 0.5 pulses/s) (5.2.1).
- Use of automatic storage of fluoroscopy images, as ‘last image hold’ or, better yet, automatic storage of all fluoroscopy sequences (5.2.1). Documentation of high-exposure images should be omitted if not explicitly required for diagnostic purposes.

<u>Voiding cystourethrography (VCUG)</u>

As with all fluoroscopy examinations, the indication for VCUG is established following a standardised approach according to the current AWMF guidelines (AWMF: Association of the Scientific Medical Societies). On principle, contrast enhanced voiding urosonography (ceVUS) should be considered as an alternative procedure. Both the indication for and the performance of VCUG should follow standards that are defined in an SOP and should include collimation, choice of projections and the number of examination cycles.

<u>Oesophagus barium swallow and small bowel follow-through (SBFT)</u>

In the context of radiation protection, these examinations require particular attention to the correct choice of pulse rates. High-frequency image series are generally only indicated for examinations of the act of swallowing. Postoperative imaging (following oesophageal atresia or if a tracheoesophageal fistula is suspected) may require a moderately increased pulse rate.

Colon contrast enema (CE)

There are typical indications for CE in children, e.g. suspicion of Hirschsprung disease. From a clinical perspective, it may therefore be possible to omit complete filling of the entire colon. Taking spot films in addition to the stored fluoroscopy images is generally not required. Contrast agents that are too dense have an immediate impact on radiation exposure, as the automatic exposure function causes an unnecessary increase in exposure parameters. Dilution of the contrast agent must be adapted to the individual clinical question.

The SSK recommends the following:

Fluoroscopy investigations in children should be performed with devices featuring pulsed fluoroscopy, a removable grid and additional filtering. For systems that are not equipped with a digital, dose-neutral zoom function, investigations should be carried out with the lowest possible zoom factor. Strict collimation settings that take account of the clinical question should be used. Documentation should preferably be done using the stored digital image (Last Image Hold), which usually provides sufficient information for diagnosis. The dose area product and the fluoroscopy time should be documented. When verifying the indication for a fluoroscopy examination, preference should be given to alternative procedures that offer the same level of accuracy (e.g. contrast enhanced voiding urosonography instead of voiding cystourethrography).

5.3 Computed tomography

5.3.1 Device technology and parameter settings

In recent years there have been rapid technological advancements in computed tomography systems. This has led to a heterogeneous device landscape with diverse potential for dose reduction.

The newest developments have contributed largely to lowering radiation exposure. They are, however, only effective when used consistently, which requires an optimally trained team of medical doctors, radiographers and medical physicists. A well-established dose management system that immediately shows outliers of radiation exposure can also be helpful. Suboptimal protocols, protocol mix-ups, incorrect use of dose modulation, incorrect positioning and inadequate use of patient contact shielding are the most common errors that can lead to increased exposure.

Paediatric examination protocols differ significantly from those in adults. In CT examinations, the (physical) half-value layer is three to five centimetres of body tissue. A body that is one half-value layer thinner thus only requires half the exposure to achieve a comparable image quality. The significant difference in exposure requirements quickly becomes apparent when comparing the body diameters of adults and children. For this reason, specific protocols should be in place for every age and weight category.

The most important dose indicator in computed tomography is the $CTDI_{vol}$. The dose length product (DLP), which is derived from this measure, also takes the scan length into account. For both measures, the Federal Office for Radiation Protection (BfS) has specified DRLs for frequent or high-dose examinations. The specified limits are age-dependent. A structured examination process should be implemented to evaluate these exposure parameters for every examination in order to decide whether device parameters have to be adjusted. To this end, the $CTDI_{vol}$ should be displayed on the device and on the diagnostic workstation as a DICOM tag or in a proprietary radiation dose report.

The dose values do not characterise the individual radiation exposure of a patient; instead, they refer to a standardised Perspex phantom with a diameter of 16 cm for the head region and 32 cm for the trunk of the body. For trunk examinations in children, this projects an exposure that is too low and must, in every case, be taken into account when estimating the level of exposure in children.

A phenomenon known as overranging occurs at approximately one rotation before and after the selected scan range in order to enable image reconstruction in the spiral mode. As a result, the scan range that is used for imaging, is smaller than the irradiated area. A single-slice scanning mode can be used as an alternative to the spiral mode, e.g. for cranial CT. In wide detector scanners, the impact of overranging increases particularly in short scan lengths, which are common in children. Therefore, the scan should typically be carried out using only the central detector elements (e.g. the central 16 to 64 detector elements on the z-axis) or special adaptive section collimation methods.

Besides the spatial resolution in the x-, y- and z-axis, the contrast-to-noise ratio is the most relevant factor influencing image quality. Especially in young children, it is important to increase the relatively weak object contrast and to also make it visible at higher noise levels. The most effective way to achieve this is to lower the tube voltage.

Unlike the correlation between dose and tube current [mAs], the correlation between dose and tube voltage [kV] is not linear. An increase in tube voltage from 100 kV to 120 kV with constant tube current time products increases the dose by approximately 40 %. Low tube voltages (e.g. 70 kV to 80 kV) may be expedient in examinations involving intravenous contrast agents owing to the proximity to the absorption edge of iodine (33 keV). The sudden increase in iodine absorption of photons with energies of around 33 keV results in a higher contrast-to-noise ratio. Moreover, decreasing tube voltages lead to an increase in contrast between the tissue structures, thus also improving the contrast-to-noise ratio.

The tube current modulation feature is designed to continuously adjust the dose to the different absorption properties in the scanning field. The most important basis for correct dose modulation is the scout scan (topogram, scanogram, surview etc.). The depicted diameter of the patient dictates the start value. Because the scout scan is a projection radiograph, the focus-to-object distance influences this value (zoom). For this reason, accurate positioning of the patient in the isocentre is imperative, otherwise the dose setting would deviate too much from the actual dose requirement. The effect can account for a dose increase in children of up to 34 % , depending on the body region being examined (Euler et al. 2019, Kaasalainen et al. 2014). Positioning should be verified by laser markers and, if possible, 3D cameras.

In children, particular attention must be paid to the eye lens. Effective measures that lower the risk of cataract include gantry tilt and tilting the head forward while accounting for overranging. Gantry tilting is not possible on all devices due to structural differences. Accurate positioning may also be impaired. In these cases, sectoral dose tube current modulation or eye shielding should be used in order to lower the exposure in the region of the lens. Sectoral tube current modulation can also be used to protect other organs including, in particular, the thyroid and breasts. Owing to the high sensitivity of young children to radiation, it is imperative to minimise exposure of the breasts. Details regarding the further use and effect of patient contact shielding are described in the SSK recommendation published in December 2018 (SSK 2018).

5.3.2 Justifying indication

CT examinations can contribute to diagnosing illnesses in a very short time and with a high degree of certainty. However, in children CT examinations are associated with a considerable increase in radiation exposure, especially in the region of the skull and trunk, with corresponding risks, as outlined in section 4.1.

Besides specific methods used in interventional radiology, CT thus generally ranks among the diagnostic procedures with the highest radiation exposure of examined patients. A data analysis from Germany for the period from 1997 to 2013 showed that the highest mean organ equivalent dose were found in the age group of 7.6- to 12.5-year-olds, namely 37.12 mGy ± 19.68 mGy for the brain and 41.24 mGy ± 20.08 mGy for the eye lens (Pokora et al. 2016). However, in every age group a decline in the organ dose was found over the observation period.

In the same analysis, a decrease of 29 % in the number of CT examinations was shown between 2006 and 2012. In principle, and provided the clinical situation allows this, in children preference should always be given to alternative procedures (cf. section 6) that provide a similar diagnostic accuracy. This is done within the scope of establishing the justifying indication (JI) as stipulated in Section 83 (3) StrlSchG.

In order to establish the justifying indication with great care, the clinical findings including any available previous diagnostic imaging must be reviewed prior to each CT scan. The risks must be strictly weighed against the potential benefit of CT with a view to the clinical question and the anticipated diagnostic outcome. Table 1 (see annex) lists the indications for which CT is primarily indicated (P) in the SSK recommendation, along with the indications for which CT is further indicated (F) (Table 1b, see annex) (SSK 2019). Furthermore, the current AWMF guidelines for specific illnesses should also be considered when establishing the justifying indication.

5.3.3 Child-friendly CT performance

An insufficiently performed CT examination is always associated with unnecessary or unnecessarily high radiation exposure. For this reason, preparing a CT scan in a child-friendly manner, in particular to prevent motion artifacts, correctly assessing the physiological features of children and choosing the adequate CT protocol is essential.

When planning and preparing a CT examination the child’s ability to cooperate, based on its age and development, must be taken into account. To this end, during the informed consent process the child’s parents should already be involved in the decision whether sedation is required for the CT scan. In the light of new evidence, the risk of sedation must always be considered in the decision making (Backeljauw et al. 2015).

When using rapid multi-detector CT scanners, sedation can be avoided in most cases either by using a positioning/fixation aid with infants or by facilitating cooperation through an anxiety-free environment – possibly by showing video clips beforehand – in older children (Esser et al. 2017, Westra 2019). The examination should be performed by personnel experienced or trained in dealing with children.

Furthermore, Section 121 (1) StrlSchV stipulates that written work instructions (standard operating procedures, SOP) are to be drawn up for each type of examination offered. Provided appropriate radiation protection measures (protective clothing) are observed and a dosimeter is worn, it has also proven successful to have one of the parents present in the examination room. Even if short anaesthesia or sedation frequently appear less burdensome, the hypoventilation that is associated with these procedures, particularly in the dorsobasal segments of the lungs, can lead to a decrease in diagnostic accuracy (Kino et al. 2019).

When positioning the patient, it must be ensured that extracorporeal metal foreign bodies are fully removed from the scanning field. When using fixation aids with infants, they should be positioned in such a way that the infants are unable to manoeuvre themselves outside the scanning field during the examination.

The use of patient contact shielding cannot be recommended unreservedly. While earlier studies demonstrated an effect on organ exposure, shielding does not reduce the exposure to the same extent as taking basic dose reduction measures (Nievelstein et al. 2010). Moreover, applying patient contact shielding is challenging and can adversely affect automatic exposure control (AEC) (see also section 5.3.1.).

When performing topograms, care should be taken to follow the manufacturer's instructions regarding the correct table height. See also section 5.3.1.

Examination protocols should be standardised and available for all age groups/weight categories, starting from newborns. The ALARA principle should be followed when creating and selecting the protocols. In this regard, the responsible radiologist must decide what noise level (e.g. following iterative reconstruction or image enhancement techniques with artificial intelligence in the future) is generally acceptable and adequate for the clinical question. The SOPs should describe, for example, the clinical questions for which a follow-up examination can be carried out with a reduced dose to monitor a known finding. In this regard, the DRLs should always be observed. With regard to the current scanner technology, the factors listed in Table 2 (see annex), along with their multitude of reciprocal effects, should be considered: As expected, limiting the body region of interest contributes significantly towards lowering the dose and protects unnecessary exposure of sensitive organs (e.g. eye lens, gonads, thyroid) that do not necessarily have to be in the scan range. Here, when using wide collimation and a high pitch, particular attention must also be paid to the overbeaming and overranging effect (Nievelstein et al. 2010, Sorantin et al. 2013).

When using intravenous contrast agents, single-phase examination protocols should primarily be used. To achieve optimal vascular and parenchymal enhancement, dual-bolus techniques can be recommended provided the intravenous access enables sufficient flow rates (Thomas et al. 2015). The use of dual-energy methods enables virtual non-enhanced image reconstruction or contrast enhancement without increasing the dose (Gottumukkala et al. 2019). However, depending on the device being used, this frequently doubles the scan time with possible adverse effects due to motion blur.

When using bolus tracking instead of fixed delay times, the benefit of contrast enhancement must be weighed against the partly considerable increase in exposure (Nievelstein et al. 2010). A sufficient delay at the start of the scan and at least 1-second intervals during the scans is mandatory (Sorantin et al. 2013).

The aim should be to find an optimal compromise of adjusted field of view, strict collimation, short rotation time and a high pitch that uses the full technical potential of the scanner. Depending on the scanner technology, high pitch factors may increase the overranging effect.

If an examination of structures with high intrinsic contrasts is planned due to the primary clinical question for CT, increased image noise may be acceptable. This generally enables a considerable dose reduction, especially through a reduction in the tube current in the range of 50% and more, without significantly reducing image quality (Esser et al. 2018).

Low acceleration voltages are advisable, especially for low body weights (infants/toddlers) or, for example, CT angiography, as they improve the depiction of vascular structures. They further improve the differentiation of parenchymal organ lesions with hyper- and hypovascularity relative to the surrounding tissue (Nagayama et al. 2018). However, non-enhanced CT with an unchanged tube current of 70 kV can also produce an adequate diagnostic image quality with an acceptable noise increase (Chi et al. 2021, Shi et al. 2016).

The use of AEC methods is generally advisable, particularly also for low tube voltages, in order to adequately compensate for increased noise by increasing the tube current (Nagayama et al. 2018, Nievelstein et al. 2010). Manufacturer-specific differences must be observed; the target parameters are adjusted either via a reference dose, reference images or the noise level.

The additional use of a tin filter can be recommended for high-contrast CT examinations. While simultaneously reducing noise, effective dose values similar to those of low-kV protocols can be achieved (Bodelle et al. 2017, Vivier et al. 2020).

Iterative image reconstruction (IR) can reduce the increased image noise that occurs in low-kV CT examinations. In comparison with standard tube voltages and filtered back projection (FBP), IR enables a significant dose reduction while maintaining or even enhancing image quality. Depending on the scanner generation being used, different and advanced IR technologies, such as model-based iterative reconstruction, are available (Wetzl et al. 2020). In future, artificial intelligence and deep-learning reconstruction algorithms will contribute to even better noise control without sacrificing spatial resolution (Brady et al. 2021).

5.3.4 Diagnostic reference levels for paediatric CT

The DRLs, which according to Section 185 (2) No. 2 StrlSchG and Section 125 (1) StrlSchV were determined for all common examinations to lower medical radiation exposure, must be taken into account. The current DRLs of the BfS and the European Guidelines on Diagnostic Reference Levels for Paediatric Imaging (PiDRL) Commission und Energy 2018 can be accessed under the following links:

https://www.bfs.de/DE/themen/ion/anwendung-medizin/diagnostik/referenzwerte/referenzwerte_node.html and http://www.eurosafeimaging.org/wp/wp-content/uploads/2018/09/rp_185.pdf.

The SSK recommends the following:

During computed tomography, any dose reductions should take account of the clinical question, among other things by lowering the effective tube current time product (mAs) and the voltage (kV).

For CT scans in children, appropriate examination protocols should be available and applied.

Medical doctors and technical radiology assistants should attend special continued and further training with a view to the rapid advances in dose reduction in CT scans, enabling them to apply dose optimisation measures (including iterative reconstruction, possibly also artificial intelligence) in a targeted manner and with the necessary expertise.

The current diagnostic reference levels must be observed.

5.4 Nuclear medicine methods (planar scintigraphy, SPECT, PET)

5.4.1 Technical and organisational optimisation

Besides selecting the appropriate examination method and procedure with the lowest possible exposure, a weight-adapted decrease in the amount of radiopharmaceutical activity injected should be at the foreground of optimising nuclear medicine imaging in children. For renally excreted radiopharmaceuticals, good hydration and frequent bladder voiding in particular are equally important after the examination in order to limit the bladder dose. Overall, a child-friendly and relaxed examination environment should help minimise motion artifacts and keep the duration of the examination as acceptable as possible. Nuclear medicine procedures include planar scintigraphy and tomography (single-photon emission computed tomography (SPECT) as well as positron emission tomography (PET)), frequently supplemented today by CT or MRI to correct the attenuation and provide anatomical and functional information. Especially in children and adolescents, devices that correspond to the state of the art in science and technology should be used in order to take advantage of an improved system sensitivity and spatial resolution as well as iterative reconstruction methods to reduce the activity administered.

The Society of Nuclear Medicine and Molecular Imaging (SNMMI) provides a corresponding online tool (Nuclear Medicine Radiation Dose Tool, www.snmmi.org) to estimate the radiation exposure of children. The amount of activity administered to a child is generally governed by body weight. A tabular list of reference values can be found in the publication of the DRLs (date of information: 15 June 2021) by the BfS (BfS 2021). When using modern technologies and optimised protocols, it may absolutely be possible to undercut the recommended activities without jeopardising the accuracy of the examination, e.g. PET with a very large field of view in comparison with conventional state-of-the-art devices. In hybrid devices, the contribution of the CT component to radiation exposure is dependent on whether the CT is carried out with a diagnostic intention or merely to correct the attenuation and provide anatomical information. In the latter case, the dose contribution may be small; the imaging parameters (kV, mAs) that require the lowest possible exposure to achieve these objectives should be used (otherwise see above, CT).

When using gamma camera systems for planar and SPECT imaging, multiple head systems should be used instead of single-head systems, as the more comprehensive coverage of the spatial angle results in a higher sensitivity, thus offering the potential to decrease the injected activity (except for purely planar examinations, e.g. diagnostic imaging of the thyroid or kidneys). In terms of technical features, the camera heads should have a high sensitivity for paediatric examinations. During post-processing of tomographic images, iterative image reconstruction methods should be used due to the better signal-to-noise ratio. Using adaptive filter methods in planar scintigraphy can improve image quality (Hsiao et al. 2011). In children and adolescents in particular, optimised converging collimators to increase the sensitivity would be desirable, but are unfortunately not available yet.

In addition to camera systems with crystal-based detectors, devices with semiconductor detectors (e.g. made from cadmium zinc telluride, CZT) that are suitable for radionuclides with photoemissions with energies up to 200 keV (e.g. technetium-99m, iodine-123) are increasingly available. Thanks to their improved intrinsic spatial and energy resolution, a good image quality can be achieved even when the amount of injected activity is reduced. The better energy resolution allows an even clearer separation of photopeak and scattered radiation as well as the performance of multinuclide examinations.

In PET imaging, a number of technical innovations (Table 3, see annex) can contribute significantly to improving image quality relative to the injected activity (e.g. Dickson et al. 2022, Schmall et al. 2021). For examinations in children and adolescents, 3D data acquisition should be used.

Increasingly large axial fields of view (15 cm to 106 cm are currently clinically available) increase the sensitivity of PET many times over (Cherry et al. 2018, Alberts et al. 2021). This can reduce the injected activity required and the acquisition times, which is particularly important for follow-up examinations.

The DRLs must be taken into account. Corresponding SOPs with optimised protocols based on the results achieved on site should be created; the various professional groups (medical physicists; medical and technical personnel) should be involved in this process.

Regular constancy testing of the devices according to the current DIN standards is required for quality assurance purposes (DIN 6855-1, DIN 6855-2, DIN 6855-4, DIN 6855-11, DIN 6858-1, DIN 6858-2).

5.4.2 Reconstruction methods

The use of modern reconstruction methods can help to lower the amount of activity injected. Image quality can be further enhanced by applying correction parameters (see annex, Table 3). The classic method of filtered back projection is being replaced by iterative reconstruction methods (e.g. Stansfield et al. 2010).

However, new reconstruction methods can not only use the acquired image data, but can also take additional a-priori information into account. With the common use of hybrid devices (SPECT-CT, PET-CT, PET-MRT), the complementary anatomical and functional information obtained from CT and MRI will become increasingly important for reconstruction in the future. This has been the case for attenuation correction of SPECT and PET for a long time, but can be improved (Brady und Shulkin 2015, Rui et al. 2015) and can also be used for other purposes to reconstruct better images while reducing the amount of activity administered (Bland et al. 2019).

A modern field of development for clinical application is the use of artificial intelligence (AI) methods within image reconstruction. AI has potential in this area, particularly for image reconstruction of datasets with few statistics (low amount of activity administered and/or short scan times) (Wang et al. 2021). However, caution is advised, as methods of artificial intelligence are also unable to exceed the physical limits. In this case it would be difficult to recognise which of the ‘reconstructed’ information is real or created only by the algorithm.

5.4.3 Special aspects of hybrid procedures (PET-CT, PET-MRI, SPECT-CT)

Besides an acquisition of SPECT, PET and CT components that is optimised for radiation protection in children and adolescents, the interplay of the two subsystems plays a crucial role in hybrid imaging. In particular, it must be decided whether a CT component with a diagnostic quality is required for SPECT-CT or PET-CT or whether a low-dose, non-enhanced CT component is sufficient for attenuation correction and anatomical orientation (‘auxiliary CT’). The latter frequently suffices for many clinical questions, such as interim staging of cancer diseases to evaluate the response to chemotherapy. For other clinical questions, diagnostic CT can be limited to a smaller body region.

PET-MRI, which enables a lower exposure and in many cases can replace PET-CT, particularly for paediatric examinations, is also available at a few sites. For examinations of the lung, however, CT currently remains the gold standard, although MRI is making headway (Serai et al. 2021).

When using diagnostic CT (possibly with contrast agents) in combination with PET, the requirements for CT listed in section 4.3 apply.

If technically possible, when using hybrid devices partial-body CT with a diagnostic intention should be used in combination with low-dose CT of the rest of the body for attenuation correction while ensuring that no body region is exposed twice.

When imaging the brain, auxiliary CT can be omitted if the attenuation correction can be performed on the basis of mathematical correction methods. It must be noted that anatomical and functional images can also be acquired on separate devices but can still be interpreted together.

Therefore, the SSK recommends the following:

Fur nuclear medicine examinations, the focus should lie on decreasing the amount of activity of a radiopharmaceutical administered based on a child's weight relative to adults.

When using PET-CT, the need for a diagnostic CT component should be reviewed on an individual basis.

If available, PET-MRI should be given preference over PET-CT.

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Annex

A-1 Tables

Table 1a: Paediatric CT recommended as 'indicated (P)' in the 'Recommendations for medical imaging procedures' of the SSK, adopted on 27/28 June 2019 (SSK 2019)

Indication	Note
Hydrocephalus/macrocephalus	CT only in an acute situation (e.g. valve malfunction) if MRI is unavailable. To be performed as a dose-reduced CCT and with a limited scan range
Acute traumatic brain injury with neurological symptoms	CT of the skull, depending on the paediatric Glasgow Coma Scale (GCS) score, consult the paediatric traumatic brain injury (TBI) guideline for absolute and relative CT indication. Alternatively, consider an MRI for relative CT indication as provided for in the guideline. If an MRI is unavailable, a follow-up CT may be required, also if primary findings are normal.
Facial skull injury and malformation	Prior to surgical reconstruction, thin-slice imaging, possibly with 3D reconstruction.

Table 1b: Paediatric CT recommended as 'further indicated (F)' in the "'Recommendations for medical imaging procedures' of the SSK, adopted on 27/28 June 2019 (SSK 2019)

Indication	Note
Congenital disorders, malformations, metabolic disorders	No routine indication. Low-dose CT. To plan surgery for complex inner and middle ear and midface malformations
Premature craniosynostosis	No routine indication. Preoperative with 3D reconstruction (low-dose), possibly MRI with special 3D technique if available
Hydrocephalus – shunt malfunction	CT in an acute situation involving older children (see above for dose reduction) if an MRI is not available
Deafness in children	High-resolution imaging of the auditory ossicles or for special clinical questions (e.g. otosclerosis) and for planning surgery; alternatively, CBCT (dose reduction)
Headache, acute or severe, primarily subarachnoid haemorrhage (SAH), neurological deficit, papilloedema, change to level of consciousness	CT only on urgent suspicion of intracranial pressure and if an MRI is not available
Sinusitis	On suspicion of orbital phlegmon to assess whether the bone is affected if an MRI is not available. Dose-reduced technique to plan and guide surgery in the event of chronic sinusitis and polyposis
Orbital trauma	CT orbits, depending on clinical severity to confirm a fracture with sufficient trauma
Torticollis without trauma	Diagnose dislocation, atlanto-axial rotational subluxation
Limb injury	Further investigation for pelvic fractures, for transitional fractures and complex joint fractures (e.g. elbow joint, upper ankle joint, hand), and to plan/guide surgery
Joint pain	On suspicion of an osteoid osteoma; alternatively, dynamic MRI with contrast agent
Recurrent productive cough	HRCT, in individual cases. To exclude bronchiectasis
Congenital heart disorders and cardiovascular diseases	MRI/MRA/CTA depending on clinical and echocardiographic findings
Chronic pulmonary diseases	Particularly for interstitial pulmonary diseases, dose adjusted for size and weight. Possibly non-enhanced scan during inspiration and expiration, respiratory arrest
Blunt abdominal trauma	CT with contrast agent, depending on the clinic in the event of major abdominal trauma. Paediatrically adapted emergency room protocols with split contrast agent bolus and weight-adjusted dose reduction. Possibly late enhancement due to contrast agent extravasate
Palpable abdominal/pelvic mass	If MRI is not possible
Haematuria with colic	Only use dose-reduced, non-enhanced techniques to confirm calculi in select cases

Table 2: Factors influencing the dose in CT (see text for explanations)

Factor	Notes
Body region	Limiting the scanning field protects sensitive organs
Non-enhanced high-contrast scan versus soft tissue scan	Reduction of tube current in high-contrast scans
Contrast-enhanced examinations	Single-phase, if possible dual-bolus technique
FoV, collimation, rotation time, pitch	Compromise of adjusted FoV, low collimation, short rotation time and high pitch optimally adapted to the scanner
Tube voltage/current and AEC	Examinations with a low kV and AEC with an optimised protocol
Filtering	Optional spectral filtering (e.g. tin filter) advisable
Image reconstruction	If possible, dose reduction through iterative image reconstruction providing the same or even enhanced image quality compared with the standard protocol
Positioning	The positioning of the patient should be verified by laser pointer and 3D cameras. To ensure correct control of dose modulation, accurate positioning of the patient in the isocentre is an absolute requirement. Extracorporeal metal foreign bodies should be removed completely from the scanning field.

Table 3: Innovation in PET technology

Innovation	Short description
3D data acquisition	Consideration is also given to coincidence lines between two detector elements that are not located in the same axial detector ring or in two immediately adjacent rings; this increases the sensitivity.
Time-of-flight	The time resolution of the detectors used not only enables the detection of the coincidence line, but also the determination of the approximate emission point of the photons on this line.
Resolution recovery	The imaging properties of the device at the different sites in the field of vision can be measured once and taken into account during reconstruction to improve the resolution.
Silicon photomultiplier	The classic tube-based photomultipliers behind the detector crystals are replaced by semiconductor components with a digital interface.
Continuous bed motion	Table feed during the scan is continuous, enabling more homogeneous imaging and the option to optimally vary the speed depending on the respective body part.
Motion correction	Method to counter a decrease in effective resolution due to respiration or heartbeat.

A-2 List of abbreviations

AP	Anterior-posterior
AEC	Automatic exposure control
ADRC	Automatic dose rate control
ALARA	As Low As Reasonably Achievable
AWMF	Association of the Scientific Medical Societies (German: *Arbeitsgemeinschaft der Wissenschaftlichen Medizinischen Fachgesellschaften e.V.*)
BÄK	German Medical Association (German: *Bundesärztekammer*)
CT	Computed tomography
$CTDI_{vol}$	Computed tomography dose index in the scan volume
DICOM	Digital Imaging and Communications in Medicine
DLP	Dose length product
DQE	Detective quantum efficiency
DRL	Diagnostic reference level
FDD	Focus-to-detector distance
FoV	Field of View
IR	Iterative image reconstruction
CE	Contrast enema
LNT	Linear-no-threshold
LIH	Last Image Hold
VCUG	Voiding cystourethrography
SBFT	Small bowel follow-through
MRI	Magnetic resonance imaging
MTRA	Medical-technical radiology assistant
VUS	Voiding urosonography
ODD	Object-to-detector distance
PA	Posterior-anterior
PET	Positron emission tomography
JI	Justifying indication
SAR	Specific absorption rate
SOP	Standard operating procedure
SPECT	Single-photon emission computed tomography
StrlSchG	Federal Radiation Protection Act (German: Strahlenschutzgesetz)
StrlSchV	Ordinance on the further modernisation of radiation protection legislation (German: Strahlenschutzverordnung)