Optimizing image quality and dose in digital radiography of pediatric extremities

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Radiography of extremities of very young patients poses specific challenges: On one hand these anatomies show only little intrinsic contrast because of the still immature bone development. On the other hand children are more sensitive to radiation than adults because of the more rapidly dividing cells and the longer life expectancy.

Optimization of x-ray imaging parameters must be guided by the ALARA principle (as low as reasonably achievable) [1]. That means that the dose to the patient should be at the lowest level that still guarantees a sufficient diagnostic image quality.

In this White Paper the optimization of image quality and dose for digital radiography of pediatric extremities is investigated. The results show that compared to conventional imaging techniques the image quality can be improved at fixed patient dose by lowering the tube voltage to 40 kV and avoiding any additional prefilter. Alternatively, if the image quality is already diagnostically sufficient the patient dose can be reduced by using the adjusted technique factors.

PHILIPS
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Optimization in conventional screen-film imaging

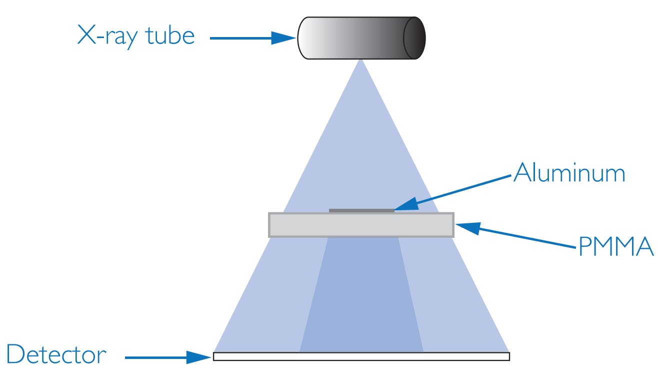
Conventional radiography is characterized by the sensitivity of the screen-film image receptor used. This necessitates a certain image receptor dose to produce a useful image, e.g., 2.5 μGy for a 400-speed screen-film system. If the patient dose shall be reduced, the receptor dose required for the correct film density must still be maintained. This can be achieved by using radiation with harder beam quality which is less absorbed in the patient. Typically, the choice is to increase the tube voltage and possibly to insert an additional filter, e.g., 0.1 or 0.2 mm copper. The use of additional filtration in pediatric radiology has even been made part of official guidelines in certain countries [2]. Depending on the type of examination, a reduction of skin dose of up to 45% and a reduction of effective dose of up to 25% can be realized with added beam filtration and increased tube voltage [3]. The dose savings are smaller for thinner body parts.

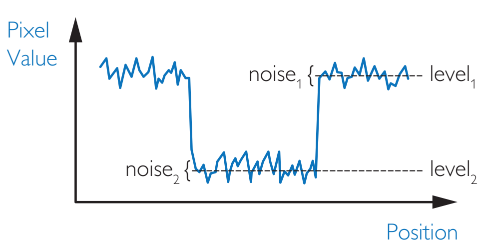
However, added filtration may have a negative effect on the image quality. Harder beam quality leads to less contrast in the image and, consequently, to a reduced contrast-to-noise ratio. While this side effect is often accepted as unavoidable and usually deemed less significant, it means that dose reduction in conventional imaging comes at a certain cost.

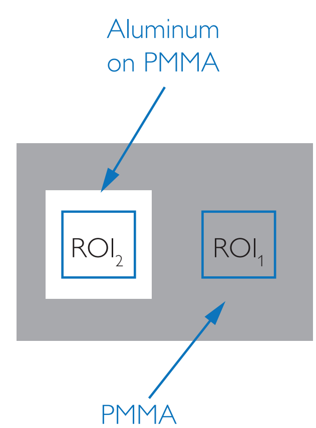
Optimization in digital imaging

With the advent of direct radiography (DR) imaging, conventional screen-film techniques for pediatric imaging

Box 1: Contrast-to-noise ratio (CNR) determination







$$CNR = \frac{level_1 - level_2}{\frac{1}{2}(noise_1 + noise_2)}$$

For **contrast-to-noise ratio (CNR)** determination an image is acquired which contains a contrast step generated by an aluminum plate of 1 mm thickness on a 1 cm PMMA slab.

Two regions-of-interest (ROI) of 100 x 100 pixels are defined in the image, one outside and one within the area generated by the aluminum plate.

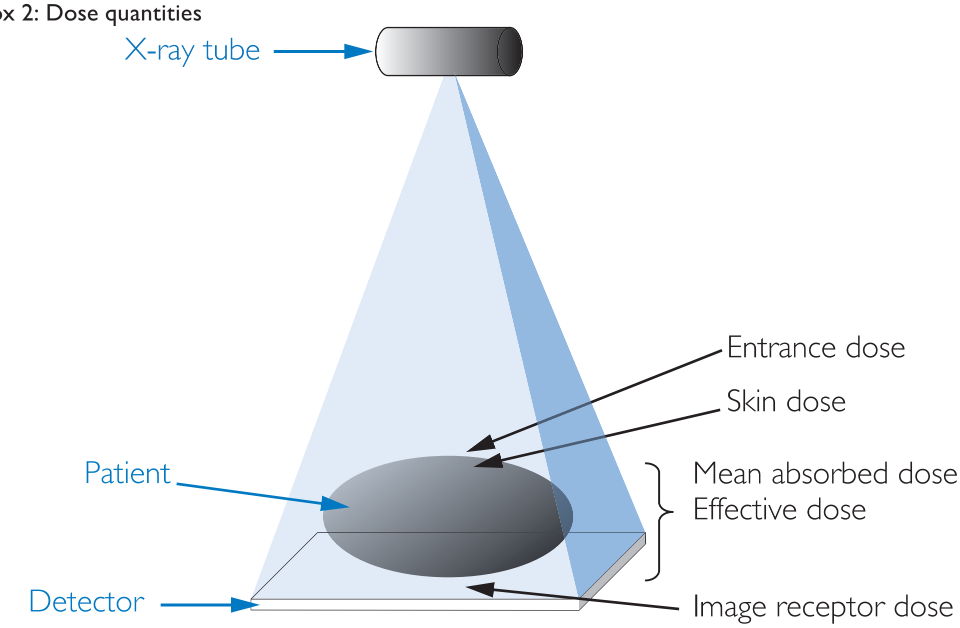
In the equation for CNR $level_1$ and $level_2$ are the mean pixel values of the corresponding regions of interest and $noise_1$ and $noise_2$ are the standard deviates from the corresponding mean values in ROI_1 and ROI_2.

The CNR defined this way is a commonly used measure for image quality and is independent of brightness and contrast adjustments (window-level and window-width) since these changes are eliminated by the given definition.

have often been carried over without change. However, digital radiography imaging has opened up new possibilities for optimization of dose and image quality. Firstly, digital detectors have a wide dynamic range, which allows capturing x-ray images at various levels of exposure. Thus, a certain detector dose is no longer a boundary condition of optimization. Also, digital imaging systems include image processing means that make it possible to freely adjust image contrast and brightness. The limiting factor is the noise level in the image which in turn is connected to the dose. The relation of both factors, contrast and noise, can be described by the contrast-to-noise ratio (CNR). Optimization in digital x-ray imaging therefore means to find the best balance between the contrast-to-noise ratio (CNR) in the image and the applied patient dose [4]. For any given detector, optimizing the x-ray parameters means to find the tube voltage (kV) and filter settings that require the lowest patient dose for a given contrast-to-noise ratio or alternatively that gives the best CNR for a fixed patient dose.

In fact, such optimization studies have been done both theoretically and experimentally for different areas of digital pediatric radiology, e.g., fluoroscopy [5] and cardiac imaging [6].

Box 2: Dose quantities



Air kerma measures the kerma *(kinetic energy released in matter)* in air in μGy, i.e. the dose without any scatter effects. It can be measured readily by commercial dose meters.
Entrance dose is the air kerma in front of the patient excluding any back-scatter. It is the effect of x-rays on a thin slab of air with no scattering object behind it.
Skin dose measures the absorbed dose to the skin of the patient including all scatter effects. It cannot be measured directly and is usually estimated using appropriate conversion tables.
Mean absorbed dose, MAD, is the absorbed x-ray energy divided by the irradiated mass measured in μGy. It is a relative measure for the risk of the irradiated tissue.
Effective dose is a patient risk equivalent measure in μSv. It takes the mean absorbed dose, irradiated area, type of radiation and the sensitivity of the irradiated tissue into account.
Patient dose is used as a general term for radiation load to the patient. It can be quantified as skin dose, mean absorbed dose, or effective dose.
Image receptor dose is the air kerma measured behind the patient directly in front of the image receptor in μGy. For films this value is important to gain an optimal optical density, for digital systems it is a measure for image-quality. E.g. for speed class 400 a typical image receptor dose is 2.5 μGy.

The CNR is derived from the pixel values in an image that contains a contrast step, which is generated by an additional absorber material (see Box 1, "CNR determination"). The patient dose D can be quantified by different dose parameters [7]. Typical choices are the skin dose, the absorbed dose, or the effective dose (see Box 2, "Dose quantities"). The skin dose is well suited as a risk indicator for deterministic radiation injuries, e.g. skin erythema. However, such injuries are uncommon at diagnostic dose levels. The stochastic risk (i.e., the probability of late after-effects of radiation exposure, e.g., development of cancer) is best quantified by the effective dose. Unfortunately, effective dose cannot be measured directly but must be derived from the entrance dose (air kerma) and the examination parameters, like exposed anatomical area, tube voltage and filtration. Typical modeling software to determine effective dose levels is based on Monte Carlo simulation [8].

Optimizing the beam quality for digital imaging of pediatric extremities

In a lab experiment the beam quality dependence of CNR and dose for an imaging situation comparable to pediatric extremities was investigated by using a 1 cm slab of polymethyl methacrylate (PMMA) as absorber representing soft tissue and 1 mm aluminum as additional contrast object representing bone. The CNR was determined from the mean and the standard deviations of the pixel values inside and outside the area of the contrast object (see Box 1 for details). The dose was measured as incident air kerma and converted into mean absorbed dose (MAD) using a Monte Carlo simulation program.

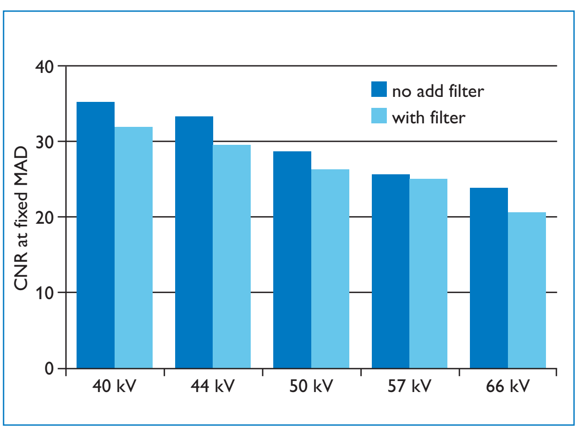


Fig. 1: Influence of tube voltage and pre-filter (0.1 mm Cu/1 mm Al) on the contrast-to-noise ratio at fixed mean absorbed dose (MAD = 25 µGy).

Fig. 1 shows the CNR at fixed MAD when varying the tube voltage, both for the situation without added filtration and with an added pre-filter of 0.1 mm Cu / 1 mm Al. The CNR is highest at 40 kV, the lowest attainable tube voltage, without added filter. Compared to a conventional setting of 57 kV in combination with the pre-filter the CNR can be increased by 42% at 40 kV without any dose penalty.

The data allow also investigating the potential for the patient dose reduction when keeping the CNR level fixed (Fig. 2). Reducing the tube voltage from 57 kV to 40 kV and removing the added pre-filter reduces the patient dose (MAD) by 56% – i.e., to less than half the dose! – while the CNR remains on the same level.

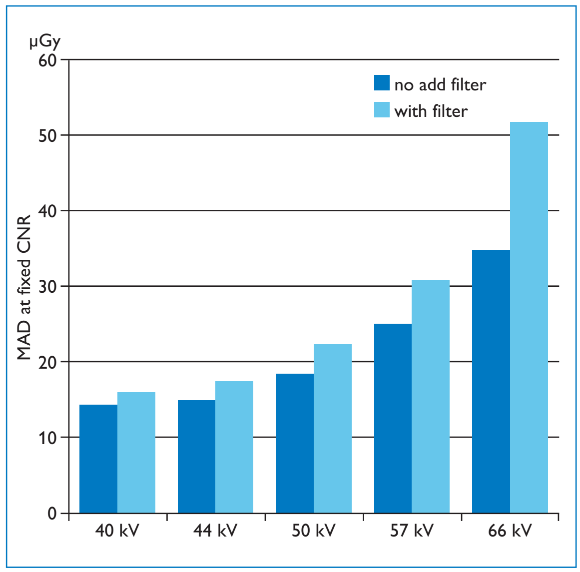


Fig. 2: Influence of tube voltage and pre-filter (0.1 mm Cu/1 mm Al) on the mean absorbed dose for a fixed contrast-to-noise ratio (CNR = 26).

Of course it is also possible to exploit the better CNR-dose relation at 40 kV in a way that leads to both image quality improvement and dose reduction, but then to a lesser degree than the extreme values given above.

It is important to note that the tube loading (mAs value) needs to be adjusted appropriately when changing the tube voltage. If the same patient dose shall be obtained at lower tube voltage the mAs value must be increased since the specific tube output (µGy/mAs) is reduced at lower kV. When trying to achieve exactly the same mean absorbed dose (MAD) or effective dose at a different kV value, simulation software is needed to determine the appropriate mAs setting since these doses cannot be directly measured. A target easier to achieve is constant entrance dose as this quantity can readily be measured with a dose meter. Fortunately, for thin objects like pediatric extremities the relation between entrance dose and mean absorbed dose (MAD) is almost constant for the tube voltage range considered here (Fig. 3). This means that keeping the entrance dose fixed will also keep the mean absorbed dose (MAD) almost constant (in fact, somewhat lower at lower tube voltage).

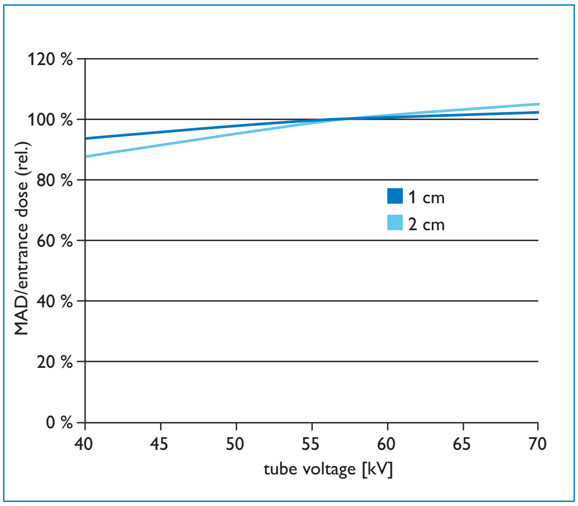


Fig. 3: Relative change of MAD per entrance dose as function of tube voltage for different thicknesses of human tissue. The reference value (100%) is set at 57 kV.

The use of anti-scatter grids is commonly avoided in pediatric imaging, especially for young patients and thin body parts like extremities. In conventional screen-film imaging grids require a dose increase and there is little to gain since the level of scattered radiation is low. In digital imaging the dose increase can be avoided because of the large dynamic range of the detector, but the question remains if there is a difference in CNR in situations with and without grid. Fig. 4 shows that for the investigated set-up (1 cm PMMA, 12:1 grid) the grid reduces the CNR for all tube voltages by about 7-10% at fixed patient dose. A grid should therefore not be used for pediatric extremity work.

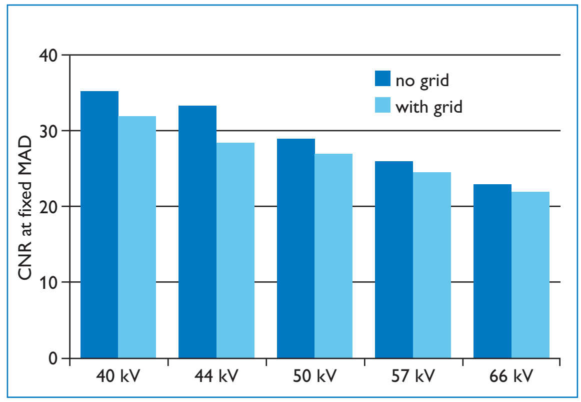


Fig. 4: Influence of the use of an anti-scatter grid on the contrast-to-noise ratio at various tube voltages. The patient dose (MAD) is kept constant (MAD = 25 μGy) for all cases.

It is also important to understand that the image receptor dose will decrease when reducing the tube voltage and maintaining a fixed dose to the patient. For the situation discussed above (57 kV → 40 kV) and fixed patient dose, the detector dose will decrease by about 10%. Together with the reduced sensitivity of screen-film systems at low kV this would lead to underexposed film images in conventional imaging. This is the reason why the low kV technique cannot be applied in conventional imaging without increasing the dose level. Digital detectors can handle the different dose and signal level easily due to their wide dynamic range while the contrast and brightness of the image can be properly adjusted by image processing.

Other conditions to optimize

Optimizing the imaging conditions for pediatric extremities is not limited to the most suitable choice of tube voltage and filtration. Other important considerations are the use of an anti-scatter grid and the use of the most appropriate patient/detector positioning device.

Different system configurations (Bucky table with fixed detector, tiltable wall stand with fixed detector, or portable wireless detector on table top) can be used for positioning the patient. Their influence on image quality and dose is mainly determined by the absorption characteristics of the patient support, i.e., table top or housings. Any absorbing material between the patient and the detector reduces the image forming radiation and leads to a reduction of the CNR. To compensate for this CNR reduction the dose would need to be increased by a corresponding factor. Also, these materials often have internal structures which may show up in the image especially at low kV and possibly interfere with the diagnostic details.

The best choice for pediatric extremity examinations is therefore to use – whenever possible – the uncovered portable detector, or, if not available, at least to avoid the table top and do the examination on the tiltable wall stand. Also, any additional sheets or mattresses beneath the patient should be removed.

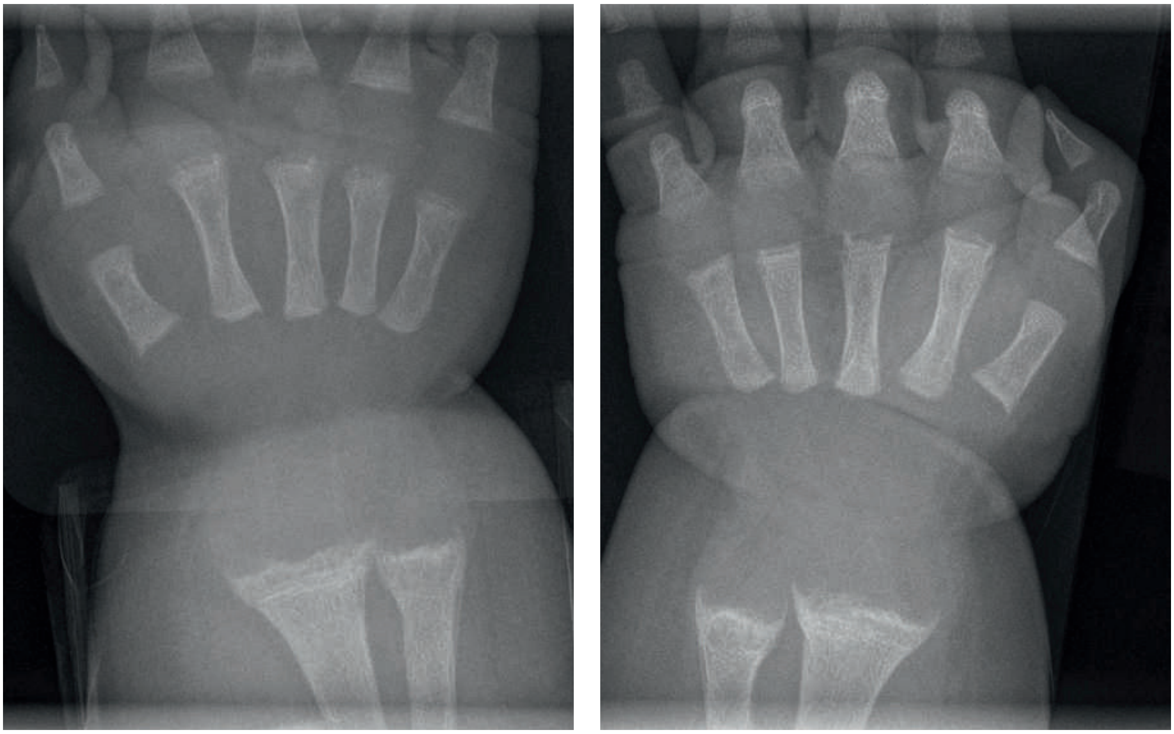


Fig. 5: Example of pediatric hand ap examinations at 50 kV (left) and 40 kV (right) with equivalent mean absorbed dose.

Clinical experience

First clinical experience at multiple pediatric hospitals shows that the image quality of pediatric extremity examinations can be substantially improved by the low kV/no filter technique without increasing the patient dose (Fig. 5). One of the pediatric radiologists using the new settings, Dr. Nancy Fisher of Gillette Children's Specialty Healthcare, Minnesota, stated: “I am very satisfied with the new images. They have helped greatly with our tiniest patients, especially with small cortical lesions, exostoses, and subtle changes due to trauma.”

Conclusion

The dose efficiency for digital radiography examinations of pediatric extremities can be improved by reducing the tube voltage to 40 kV and avoiding any additional pre-filter. This is in contrast to conventional screen-film pediatric x-ray imaging where additional filtration and increased tube voltage are seen as means to reduce patient dose. The improved protocol can be exploited either for maximizing the image quality (CNR) at a given patient dose or to reduce the dose level while maintaining the contrast-to-noise level in the image.

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Glossary

ALARA	as low as reasonably achievable
CNR	contrast-to-noise ratio
kV	kilo volt, unit of x-ray tube voltage
MAD	mean absorbed dose
mAs	milli Ampere seconds, unit of tube loading (current time product)
µGy	micro Gray, unit of radiation dose
PMMA	polymethyl methacrylate (acrylic glass)

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