

Optimization of pulsed fluoroscopy in pediatric radiology using voiding cystourethrography as an example

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► **Small children are about ten times more sensitive to radiation than middle-aged adults.**

In the 11th “Report on Carcinogens” of the United States National Toxicology Program [1], X-irradiation and ionizing irradiation were placed on the list of known human carcinogens. This fact caused at least some confusion in the United States and led to a statement by the Radiologic Society of North America. This discussion was set in motion by a report by Pierce and Preston in 2000 on “Radiation-related Cancer Risks at Low Doses among Atomic Bomb Survivors” [2], as well as by this finding being featured in the national press [3].

Radiation hygiene has an especially large role in the case of pediatric patients. Small children are approximately ten times more sensitive to radiation than middle-aged adults. The higher radiation risk in children arises on the one hand from the longer life expectancy, and on the other it is clearly correlated with the high radiation dose to the organs in children compared with adults subjected to comparable X-ray examinations [4-6].

Nevertheless, the above-mentioned reports were not a motive, but a confirmation, of the need for the continued intensive effort to optimize X-ray examinations in children in accordance with the ALARA principle (As Low As Reasonably Achievable). The ALARA principle was first introduced by the United States Nuclear Regulatory Commission in order to limit the radiation burden on occupationally exposed

individuals, rather than that on patients [7]. This principle was then carried over by radiologists to the exposure of patients.

The earlier studies [4-6] described the radiation dose reduction measures employed to limit the radiation burden in pediatric patients during fluoroscopic examinations, especially with respect to voiding cystourethrograms (VCUs). It is easy to decrease the radiation burden by reducing the image intensifier entrance dose, by using shorter fluoroscopy times etc., but it is more difficult to do this while maintaining acceptable imaging and diagnostic quality.

When grid-controlled fluoroscopy became available for applications in pediatrics as a technology to reduce radiation dose, while simultaneously improving the diagnostic image quality [8, 9], the Department of Pediatric Radiology at the University of Mainz in Germany undertook to examine this new technology with regard to its medical relevance.

Materials and methods

This study was carried out using a standard over-table fluoroscopy system (Philips Diagnost 96, Eindhoven, the Netherlands) with triple-format moveable 38 cm image intensifier and digital fluoroscopy chain (digital spot imaging (DSI). The digital television chain has the last image hold option (LIH). The X-ray generator

Table 1. Dose-area product (DAP) values for the various fluoroscopy modes [L1]. The DAPs were determined with the facility's own M2 Diamentor, PTW, Freiburg, Germany. 25 mm Al was used as the test object. All measurements were determined with an irradiation time of 30 seconds.

Pulse rate	Adult patient characteristic curve DAP for D	Adult patient characteristic curve DAP for D/2	Pediatric patient characteristic curve DAP for D	Pediatric patient characteristic curve DAP for D/2
Hz	cGycm ²	cGycm ²	cGycm ²	cGycm ²
Cont.	98	54	---	---
6.25	53	28	23	14
3.13	29	17	13	8
1.56	17	8	7	5

has grid-controlled fluoroscopy with four frame rates: continuous, 6.25, 3.13 and 1.56 Hz. The corresponding image intensifier dose rates are: 0.24, 0.20, 0.14 and 0.10 $\mu\text{Gy/s}$. Using an additional function, all image intensifier dose rates can be decreased to half the values specified. The cut-off dose for spot images via the image intensifier is 0.66 μGy . For fluoroscopy, the user can choose from two kV/ mA characteristic curves. One characteristic curve with a typical 20 ms pulse width can be used for standard examinations (adult characteristic curve). The second characteristic curve (pediatrics) with a typical pulse width of 10 ms is adapted to the specific pediatric requirements. This special characteristic curve ensures that, as a rule, the examination kV limit of 70 kV is maintained, even for the smallest subjects (infants). The focus-detector distance is 110 cm.

Even though the anti-scatter grid could be easily removed as required, all examinations, except for those in neonatal patients, were conducted with a stationary carbon fiber anti-scatter grid (N 60, r 13, f 120) [10].

Other dose-relevant technical factors in the imaging system include:

- digital spot imaging (DSI) via the image intensifier
- grid-controlled fluoroscopy (GCF) for regulation of the dose rates for pulsed fluoroscopy within the pulse duration
- image quality exposure (IQX) for radiation dose regulation in digital spot imaging
- additional 0.1 mm Cu and 1 mm Al pre-filtration
- adaptive correction of field measurement (ACFM) for all fluoroscopy modes and DSI [8].

The dose-area product (DAP) values of the various modes, as measured in our facility, are listed in Table 1. The 14 fluoroscopy modes shown in this Table are based on the rationale of giving the examiner the choice between a higher contrast fluoroscopic image quality at a lower tube voltage (adult patient characteristic curve) or a fluoroscopic examination focusing on a lower radiation dose level at higher tube voltage (pediatric patient characteristic curve) allowing

for lower contrast in the object and image. The examinations of the GCF long-term study were conducted in the period from January 1, 2003 to December 31, 2004 by three experienced pediatric radiologists who had also conducted a previous study [11]. Since fluoroscopic examinations, and the assessment of the clinical image quality, are always examination-dependent, one of the prerequisites of a long-term observation is the consistency of the examiners and thus of the examination processes, as was the case here. The diagnostic image quality was assessed by the examiner. In this case, care was also taken to ensure the image quality was verifiably sufficient.

A regular consistency check ensures that the respective settings have not changed during the VCU study. For the long-term study, the DAP was measured at each patient examination with the M2 Diamentor (PTW, Freiburg, Germany) and added to the documentation.

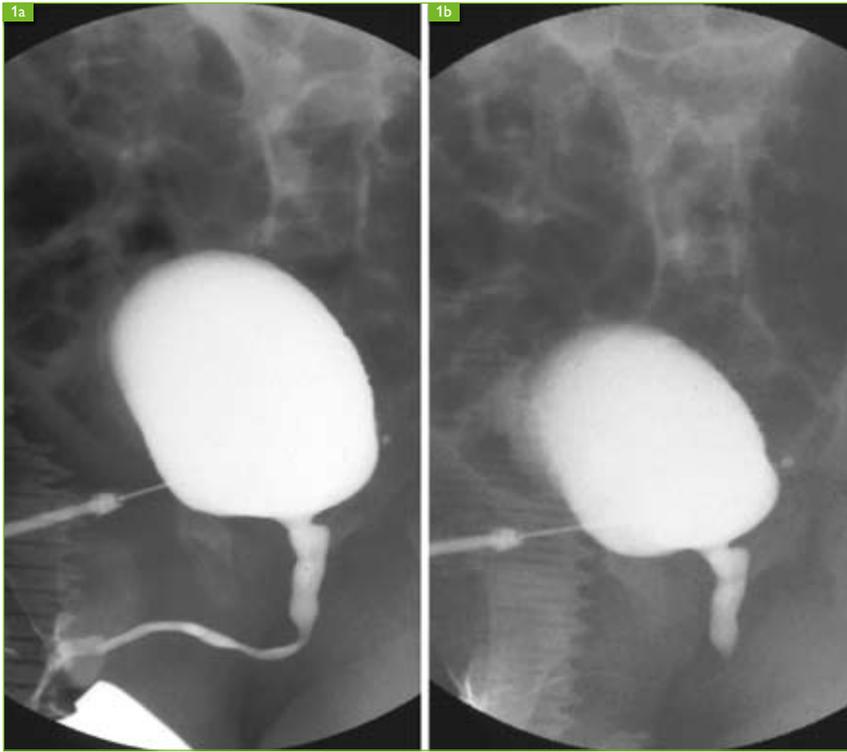
All VCUs were evaluated from the period specified above with respect to the radiation dose requirement (DAP). For this purpose, the patients were divided into three age groups: less than 1 year, 1 - 5 years and over 5 years. The contrast agent for the VCU was delivered to the bladder by means of suprapubic bladder puncture. The filling phase of the bladder was observed using only a single radiation pulse, while voiding was observed under continuous pulsed fluoroscopy at 1.56 Hz. The studies were documented almost exclusively using fluorograb images from the fluoroscopy. Where spot images were acquired, this was done separately. Almost all the examinations were carried out with the anti-scatter grid in the X-ray beam. Documentation was done on laser film.

For almost all examinations, the operators chose the pediatric patient characteristic curve, with a pulse rate of 1.56 images/second and the image intensifier dose rate D/2. Despite this selection, the image quality of the individual fluoroscopic pulse images was still sufficient to produce diagnostic-quality documentation from the fluoroscopy (LIH or fluorograb) images. This was repeatedly documented by a comparison between LIH images and digital spot images

► **Diagnostic-quality images could be obtained from the fluoroscopy images.**

Table 2. Age-dependent dose-area products (DAPs) for voiding cystourethrograms (VCUs) from the GCF/IQX long-term study from January 1, 2003 to December 31, 2004. The figures show the means and standard deviation () of the DAP (specified in cGycm^2) for pulsed fluoroscopy and last image hold option (LIH) documentation for VCU in pediatric patients. The DAPs for three age groups are compared with the respective current diagnostic reference values [12].

	n	DAP < 1 year	DAP 1 - 5 years	DAP > 5 years
Pulsed fluoroscopy (1.56 Hz)	584	3.2 (2.3)	4.8 (3.1)	11.4 (11.9)
Diagnostic reference values [11]		90	120	240



▲
Figure 1. Voiding cystourethrogram (VCU), Male infant, 2 months.

Figure 1a. Indirect image from image intensifier (IQX).

Figure 1b. Fluorogram documentation immediately following Figure 1a.

The gray scale has been inverted for comparison purposes.

made at the same time. The high quality of the LIH and fluorogram images made it possible to dispense with the digital spot images almost completely (Figure 1a and 1b).

Results

During the specified period between January 1, 2003 and December 31, 2004, 584 VCUs were carried out with the GCF/IQX technology and the data were evaluated with respect to the three age groups (n = 179 < 1 year, n = 254 1 - 5 years and n = 151 > 5 years) (Table 2).

Diagnostic reference values for specific examinations correspond to the 75th percentile from a large, multicentric survey of radiation dose values. Thus, they also correspond to the current German standard [12].

Over 95% of all the examinations could be carried out exclusively using the pediatric patient characteristic curve, a pulse rate of 1.56 Hz and an image intensifier dose rate of 0.10 $\mu\text{G/s}$. Here the anti-scatter grid was always in the X-ray beam. The image quality of the LIH images was good enough that they were used for documentation purposes. No digital images were required for this group.

For the examination of premature infants and neonates, the pediatric patient characteristic curve was also chosen with a pulse rate of 1.56 Hz. Here, the image intensifier dose rate was decreased from 0.10 $\mu\text{G/s}$ to 0.05 $\mu\text{G/s}$ (D/2). The anti-scatter grid was removed from the X-ray beam before the examination. In a few cases, digital images had to be made for documentation.

For pediatric patients over 5 years old, the examinations were first started using the pediatric patient characteristic curve, a pulse rate of 1.56 Hz, an image intensifier dose rate of 0.10 $\mu\text{G/s}$ and the anti-scatter grid in the X-ray beam. In rare cases, a higher image quality (adult patient characteristic curve) was briefly selected during the examination. Table 3 illustrates the high radiation dose saving potential of the GCF/IQX technology. It shows the development of the DAP over a period of 15 years [11-13] and the radiation dose

	n	DAP/% < 1 year	DAP/% 1 - 5 years	DAP/% > 5 years
a. Diagnostic reference values as of 2005 [12].		90/100	120/100	240/100
b. 100 mm technique and continuous fluoroscopy to 1993 [11].	101	44/49	93/78	132/55
c. Digital imaging and continuous fluoroscopy to 1997 [13].	40	54	99	210
d. DSI and pulsed fluoroscopy (1.56 Hz) as of 2003.	584	3.2/4	4.8/4	11.4/5

▲
Table 3. Compilation of method-dependent and age-dependent dose-area products (DAPs) (cGycm^2) for voiding cystourethrogram (VCU) results of the long-term study as of 1990 and information from the relevant literature. The % values are related to the diagnostic reference values in (a) below.

a. Diagnostic reference values for specific examinations correspond to the 75th percentile from a large, multicentric survey of dose values [12].

b. 100 mm technique on an under-table system with continuous fluoroscopy and 0.2 mm Cu pre-filtration without anti-scatter grid in the X-ray beam (before 1993) [11].

c. Digital spot imaging (DSI) with an over-table system with continuous fluoroscopy and 1 mm Al + 0.1 mm Cu pre-filtration [13].

d. DSI on an over-table system with pulsed fluoroscopy and 1 mm Al + 0.1 mm Cu pre-filtration and high line grid (from 2003).

reduction due to the introduction of pulsed fluoroscopy with the pediatric patient characteristic curve.

Discussion

The direct relationship between the image dose level and the image quality attained has been long known and is highlighted again and again when innovative imaging systems are used [14, 15]. Thus the question as to the image quality required has always been answered to the effect that we need exactly the image quality that enables the required diagnosis to be made. In order to make this possible, four different image qualities can be selected (two characteristic curves and two) in each pulsed fluoroscopic mode (Table 1).

Given the correct application parameters, DSI should meet the same criteria as other imaging techniques: the best image is the one that answers the medical question at hand with the lowest radiation dose.

The study by Kuon et al. [16] impressively demonstrates that not only the technique and the equipment design can contribute to radiation dose level reduction but also, and in particular, the operator. Kuon shows that consistent collimation alone can reduce the DAP by between 46% and 65%. Unfortunately, this conclusion is only valid for systems with adaptive correction of field measurement ACFM. In systems without an adaptive measuring field, collimation (decreasing the irradiated area) results in upward adjustment of the dose rate (recognizable because areas of low density are overexposed so that information is lost). Without a technique like ACFM, infants especially are subjected to an increased radiation dose of up to a factor 5 for consistent collimation as compared with the situation without collimation. Using the ACFM available in this study enabled the radiation dose to be cut with each collimation, i.e. half the area: half the DAP.

The switch to pulsed fluoroscopy is not trivial. There is a learning curve required to understand the paradigm shift in imaging and to become accustomed to examinations where an image of the subject being examined is obtained only about every 0.6 seconds. The gaps between the images are bridged by freezing the last image (gap filling) without any flickering. Obviously, the swallowing process in patients cannot be studied at such slow frame rates. On the other hand, examinations of the urogenital and gastrointestinal tract, including the esophagus, are easily possible [9]. Examinations of the

various organs, and the pylorus and duodenum in children, permit the frame rates to be reduced to the lowest value of 1.56 Hz without any loss of the detail important for diagnosis.

Consideration should be given to the fact that the visual pathway results in the eye-brain integration system only noticing an image about every 0.2 seconds, even with continuous fluoroscopy, so that the continuous visual impression is compounded to all intents and purposes from a sequence of stroboscopic “experiences” (images). Consequently, continuous fluoroscopy offers no advantage from the viewpoint of the physiology of vision [17, 18].

In order to ensure examiners have the same impression of the image with pulsed fluoroscopy as with continuous fluoroscopy, further factors of vision physiology [17-19] must be taken into consideration.

At high frame rates, the contrast resolution of the visual system drops. Since image noise represents low-contrast “information”, it is not detected at high frame rates. If the frame rate is decreased, the contrast sensitivity of the visual system [20] increases up to a frequency of 5 Hz. Low contrasts, such as noise, are detected and are distracting. In order to compensate for this impression, an increase in the signal-to-noise ratio is required to improve the image quality. In diagnostic radiology, this requires an increase in the radiation dose used to form the image for a single frame. Thus, when the frame rate is halved from continuous (25 full fps) to 12.5 fps, the image intensifier dose rate must not be reduced to 50%, but to 80%, and at 6.25 Hz it must not be reduced to 25% but to 58%. This frequency-dependent image intensifier dose rate adjustment is described as the eye integration factor (EIF). Like any physiological factor, the EIF varies slightly for each operator [18, 19]. The eye integration factors selected for our system for 6.25, 3.12 and 1.56 Hz yield an image intensifier dose rate of 0.20, 0.14 and 0.10 $\mu\text{Gy/s}$. The necessity of increasing the radiation dose of the single pulse has two consequences:

- The theoretically possible radiation dose-saving effect of the image intensifier dose rate is partly used up again by the EIF (the theoretical radiation dose of a single pulse is 1/25 of the dose/second for continuous fluoroscopy; because of the EIF, the image intensifier dose rate is reduced to 40%, not just 5%, at 1.56 Hz).
- The single frame radiation dose increased by the EIF is another reason for the greater contrast and better detail of all pulse images. The signal-to-noise ratio improves, making the

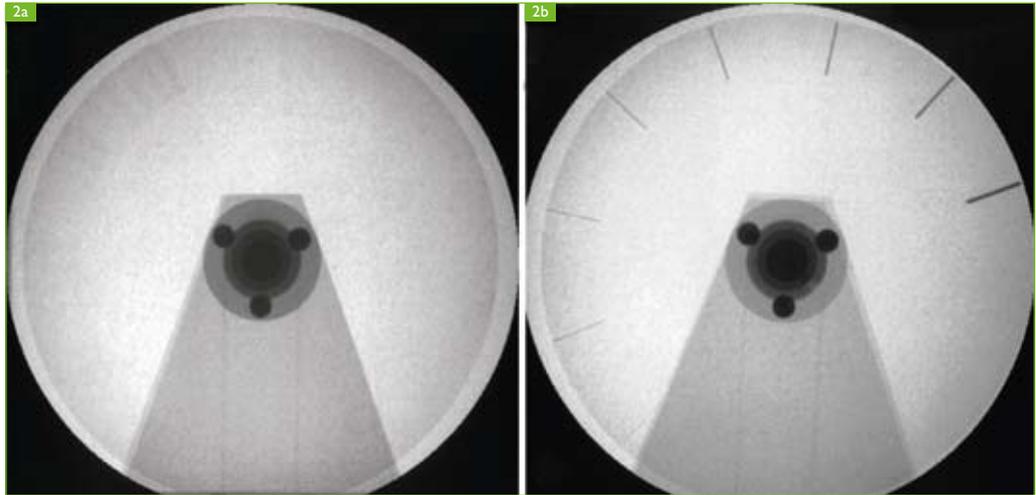
► **The switch to pulsed fluoroscopy requires a learning curve.**

► **Factors of vision physiology must be taken into consideration.**

▶ Figure 2. Rotating disc with an angular velocity of 100°/s.

Figure 2a. Continuous fluoroscopy with recursive filtration: Blurred contrast bands with stroboscopic effect at 11 o'clock. The target was read out 25 times per second with continuous fluoroscopy. The new image data is added to the after-image data already present on the target. Since the disc rotates in a clockwise direction, the slowly fading fringe patterns to the left of the first band correspond to the decreasing remainder data on the target, thereby creating a stroboscopic effect, in this case increased by the recursive filtration. The somewhat greater background brightness when compared to Figure 2b is also due to the remaining data on the target.

Figure 2b. Pulsed fluoroscopy (GCF) 8-9 sharp, well delineated contrast bands visible. Background brightness is somewhat less than in Figure 2a.



fluoroscopic image quality obtained sufficient for diagnostic purposes. Hence, the production of spot images (IQX) becomes unnecessary to a great extent.

A very favorable effect seen in examinations is the fact that, in 50% of examinations, a normal, acceptable image is already obtained with the first pulse, and at the latest it is present with the second pulse. This substantially shortens the time required for fluoroscopy. This is made possible by an in-pulse regulation of the dose rate, which still has an immediate effect on the same pulse. In some cases, the whole examination can therefore be completed within 16 - 32 pulses, which is equivalent to a total irradiation time of 160 - 320 ms.

The grid-based control of the tube is a major factor in reducing the radiation dose. Due to the short pulse width of typically 10 ms in pediatrics, this not only makes generating images possible without any blurring due to movement (Figure 2), but also, in contrast to generator-controlled pulse production, generates pulses with steep flanks, thus solving the “ramp and trail” problem [21]. In the case of small subjects (pediatric patients), the steepness of the flanks results in considerable savings in radiation dose.

A fluoroscopic technique that produces an optimum image contrast with a minimum radiation dose must have a different combination of kV and mAs in neonates and infants than in adults. For neonates and older pediatric patients, a special pediatric patient characteristic curve was created [8, 22, 23], which controls the kV for the same subject in contrast to a traditional kV/mA characteristic curve at a higher value.

The dose rate is controlled to correspond to a (pediatric) control curve especially adjusted to save radiation doses. When a higher radiation

dose is required the tube voltage is first increased before starting from 70 kV, and then the tube current (mA) is also increased [8]. While the tube current has a linearly proportional effect on the dose rate, increasing the voltage results in an exponential increase in radiation dose and the radiation becomes harder, so that the required patient entrance dose can be decreased for a constant radiation dose requirement at the image receptor [8, 19, 21].

The German standard DIN 6809-7 states that for the same subject at 70 kV, the patient entrance dose is about 74% lower than at 50 kV [23]. This documents the disproportionate effect that a characteristic curve adapted for pediatrics has on radiation dose saving. The second effect of this control is evident in the lower image contrast, since the object contrast decreases as the voltage rises. Thus it is shown that the image contrast is again somewhat improved by leaving out the anti-scatter grid. However, the image contrast of small, calcium-containing structures is very low, even when using a grid. If questions need to be clarified, e.g. concerning concretions seen in fluoroscopy, the normal contrast control curve (adult patient characteristic curve) must be selected.

Although the image intensifier dose rate in this study was set deliberately higher than the technically possible minimum value, the measured average values of the DAP for our examinations were about 4% of the legal diagnostic reference value for the VCU (Table 3). The previous diagnostic image quality is not only maintained, but is improved, when the radiation dose of the individual pulses is increased.

This study shows that complying with the ALARA concept is a complex process, in which a number of factors play an equal role. These factors include the equipment design, operation

▶ **In 50% of examinations, a normal, acceptable image is obtained with the first pulse.**

of the equipment, duration of fluoroscopy, number of images, radiation dose level per image and dose rate. However, the human factor is the unifying one and can be controlled to a great extent with proper training [16, 17, 24].

In conclusion, it has been determined that in imaging with pulsed fluoroscopy, a large number of variables play a part. The consideration and use of these variables enable considerable reduction in radiation dose levels, compared to continuous fluoroscopy, with a simultaneous improvement in image quality. The operator must, in part, evaluate his or her existing knowledge in a new and critical manner. With pulsed fluoroscopy, a dramatic change occurs for perceptions based on experience with conventional imaging and continuous fluoroscopy, and the paradigms derived from these perceptions.

Until now the rule has been that for infants a consistent collimation must be carried out on the area being examined. The new paradigm is that a consistent collimation should only take place if the system has an ACFM for digital images and fluoroscopy. Until now, the anti-scatter grid had to be removed in pediatrics. The new paradigm is that the anti-scatter grid should not be removed for pulsed fluoroscopy

with a pediatric patient characteristic curve and an additional pre-filtration with 1 mm Al and 0.1 or 0.2 mm Cu. Due to the increased kV and the additional pre-filtration, the radiation is made harder and the object contrast is lowered. Without the anti-scatter grid in the path of the X-rays, more digital spot images would again have to be made for documentation purposes and the DAP would increase as a result.

A radiation dose reduction/examination of approximately 80% with a simultaneous improvement in image quality is thus achievable using pulsed fluoroscopy in pediatric patients [25]. Dose-area products will thereby be obtained that are in the range of approximately 4% of the diagnostic reference value. This has been demonstrated in our example of voiding cystourethrography.

The lack, or insufficient use, of most options for optimization available in the equipment has recently been pointed out, including the use of fluoroscopy for interventional procedures [16, 24-26]. This emphasizes the necessity for implementing the paradigm shifts identified above and imparting them through further training. Training programs should highlight these techniques that are so pertinent to reducing radiation dose level ■

► **Sharper images and an 80% reduction in radiation dose were achieved.**

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