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Impact of imaging approach on radiation dose and associated cancer risk in children undergoing cardiac catheterization

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Abstract

Objectives—To quantify the impact of image optimization on absorbed radiation dose and associated risk in children undergoing cardiac catheterization.

Background—Various imaging and fluoroscopy system technical parameters including camera magnification, source-to-image distance, collimation, anti-scatter grids, beam quality, and pulse rates, all affect radiation dose but have not been well studied in younger children.

Methods—We used anthropomorphic phantoms (ages: newborn and 5-years-old) to measure surface radiation exposure from various imaging approaches and estimated absorbed organ doses and effective doses (ED) using Monte Carlo simulations. Models developed in the National Academies' Biological Effects of Ionizing Radiation VII report were used to compare an imaging protocol optimized for dose reduction versus suboptimal imaging (+20cm source-to-image-distance, +1 magnification setting, no collimation) on lifetime attributable risk (LAR) of cancer.

Results—For the newborn and 5-year-old phantoms respectively ED changes were as follows: +157% and +232% for an increase from 6-inch to 10-inch camera magnification; +61% and +59% for a 20cm increase in source-to-image-distance; –42% and –48% with addition of 1-inch periphery collimation; –31% and –46% with removal of the anti-scatter grid. Compared to an optimized protocol, suboptimal imaging increased ED by 2.75-fold (newborn) and 4-fold (5-year-old). Estimated cancer LAR from 30-minutes of postero-anterior fluoroscopy using optimized versus sub-optimal imaging respectively was: 0.42% versus 1.23% (newborn female), 0.20% vs 0.53% (newborn male), 0.47% versus 1.70% (5-year-old female) and 0.16% vs 0.69% (5-year-old male).

Conclusions—Radiation-related risks to children undergoing cardiac catheterization can be substantial but are markedly reduced with an optimized imaging approach.

Keywords

Image optimization; effective dose; fluoroscopy; cancer lifetime attributable risk

Introduction

Ionizing radiation exposure is potentially harmful, even at the low dose exposures that typically occur during medical imaging procedures.(1-4) Epidemiologic studies have demonstrated an increased lifetime cancer risk associated with childhood exposure to computed tomography scans.(5,6) Compared to computed tomography, complex cardiac catheterization procedures in children typically require much higher doses of ionizing radiation and strategies to limit radiation burden are critically important.(7)

The approach to imaging during cardiac catheterization substantially impacts radiation dose. Imaging parameters such as periphery collimation, camera magnification, and source-to-image distance (SID), as well as technical parameters including anti-scatter grids, pulse or frame rates and the X-ray beam, can all be manipulated to alter dose.(8,9) The impact of these factors on radiation burden relates to patient size and body habitus but current understanding is largely based on analyses in adults.(10,11) No studies have evaluated the unique impact and magnitude of effect of these imaging and technical parameters on radiation dose during pediatric cardiac catheterization.

Furthermore, most of the published literature on cardiac catheterization dose in children has reported air kerma or dose area product (DAP) to quantify radiation burden.(12) These values represent exposure in air and do not account for differing levels of tissue attenuation. There are flaws in this approach when evaluating fluoroscopy in children because auto exposure controls will alter dose depending on patient size so as to maintain image quality. (13) Consequently it is likely that air kerma or DAP values inaccurately reflect differences in absorbed radiation dose when comparing patients with varying body habitus and when comparing camera angulations with differing organ exposure. In contrast, effective dose represents a weighted estimate of absorbed organ/tissue radiation and therefore provides a more meaningful comparison across the pediatric age spectrum and for comparing imaging with differing organ exposures.(1)

To overcome the limits of DAP and air kerma as dose metrics, and to estimate the relative effects of various imaging protocol variations on radiation dose, we used anthropomorphic phantoms combined with Monte Carlo simulations to estimate organ and effective doses across a range of imaging and technical parameters during pediatric cardiac catheterization. We then used models developed in the National Academies' Biological Effects of Ionizing Radiation VII report to compare the effect of an imaging protocol optimized to reduce radiation dose versus sub-optimal imaging on lifetime attributable risk (LAR) of cancer. These estimates provide actionable data that pediatric interventional cardiologists can use to optimize imaging and reduce radiation dose.

Methods

Phantoms and imaging protocol

Two ATOM family anthropomorphic phantoms (CIRS, Norfolk, VA) representing a newborn (51cm, 3.5kg, thorax dimension 9×10.5 cm) and a 5-year-old child (110cm length, 19kg, thorax dimension 14×17 cm) were used for imaging simulations. The phantoms are specifically designed for radiation dose assessment. They are manufactured using tissue/organ equivalent epoxy resins (including bone density formulated to represent the appropriate bone age of the phantom) with linear attenuation within 1% for bone and soft tissue and 3% for lung tissue at photon energies from 30 keV to 20 MeV. Imaging was performed on a Philips Allura XP FD 10/10 (Philips Healthcare, Netherlands) biplane fluoroscopy system. The system includes a removable 70 line anti-scatter grid. The phantom was positioned in the center of the fluoroscopy table and cameras were positioned by a trained pediatric interventional cardiologist to optimally simulate typical imaging views. For all imaging, a “standard operating technique” was defined to approximate typical imaging conditions. Baseline images were performed with 1” periphery collimation on all sides and the smallest possible source-to-image distance (93cm/112cm for postero-anterior (PA) and lateral fluoroscopy respectively). Unless otherwise stated, pulse rates of 15 pulses per second (pps) were used for fluoroscopy and 15 frames per second (fps) with a pulse width of 0.4 msec for cineangiography. The beam parameters (kVp and millAmperes) were optimized for the phantom age and weight using an infant (< 10 lbs) and child (25-55 lbs) protocol for the newborn and five-year-old respectively. For the newborn baseline imaging was performed with 6 inch magnification while 8 inch magnification was used for the five year old consistent with our laboratories’ typical approach. Subsequently the imaging parameters were individually manipulated with imaging repeated so as to assess the impact of each individual parameter manipulation. All imaging was performed in duplicate for 1 minute of continuous exposure for fluoroscopy and 20 seconds of continuous exposure for cineangiography. For each imaging sequence we recorded radiation-related output values from the fluoroscopy system including kVp, millamperes (mA), air kerma and DAP.

Effective dose estimations

Organ/tissue doses and cumulative effective doses were estimated from Monte Carlo simulations using PCXMC (version 2.0) simulation software (STUK, Helsinki Finland).(14) PCXMC estimates radiation dose to organs and the whole body using a mathematical phantom. It yields dosimetric estimates of primary radiation from measurements and manufacturer specifications, and of scatter using Monte Carlo calculations. The methodology has been previously published and validated and a comprehensive description is provided on the website of STUK, the Radiation and Nuclear Safety Authority of Finland (http://www.stuk.fi/sateilyn-hyodyntaminen/ohjelmat/PCXMC/en_GB/pcxmc/). Data input into the PCXMC simulation software included the phantom age, height and weight, as well as the imaging parameters including: 1) beam shape, 2) beam position over the thorax, 3) source to subject distance, 4) subject to receptor distance, 5) camera angles and 6) air kerma at the interventional reference point. Because air kerma values obtained from the phantom imaging (and also from patient imaging) reflect only emitted radiation and do not account for table attenuation, we performed a baseline assessment using a 0.18 cc ionization

chamber (Radcal Corporation, Monrovia, CA, Model # 10×5-0.18). We measured a table attenuation of 8.8% at the relevant beam quality with a peak energy of 68 kV and applied this correction factor to the PA Monte Carlo estimates. Effective doses were estimated using the weighting factors of the International Commission on Radiological Protection (ICRP) in its 2007 recommendations, i.e. ICRP Publication 103.(1) Weighted equivalent doses were determined for all organs for which individual weighting factors are assigned in ICRP 103. Dose estimates of effective dose were determined by summing these weighted equivalent doses, as well as a weighted equivalent dose reflecting the “remainder organs”.

Imaging approach and cancer risk estimates

To provide better clinical perspective we defined a series of imaging approaches as follows: 1) suboptimal imaging - 113cm SID, no collimation and high magnification (6” for the newborn and 8” for the five-year old); 2) intermediate imaging – 103cm SID, 1” peripheral collimation and high magnification (6” for the newborn and 8” for the five-year old); 3) optimal imaging – 93cm SID, 1.5” peripheral collimation and low magnification (8” for the newborn and 10” for the 5-year old); and 4) optimal imaging with technical parameters (grid removal + lowering of fluoroscopy pulse rate to 10 per second). For each of these combinations of parameters we measured effective dose and also estimated LAR of cancer. Cancer LAR was estimated using the approach of the National Academies Biological Effects of Ionizing Radiation VII report (BEIR VII).(2) Cancer risk was estimated individually for each of the cancer susceptible organ and tissue structures and then summed to provide a cumulative cancer risk estimate.

Statistical analysis

Statistical analysis was performed using SPSS 22.0 (IBM, Chicago, IL). Continuous data is presented as mean with error % representing the statistical uncertainty from the Monte Carlo simulation. Correlations between variables were determined using the Spearman rank order correlation coefficient. All tests of significance were two-tailed; a P value of less than 0.05 was considered to indicate significance.

Results

Organ absorbed doses

Table I summarizes doses to the major cancer susceptible organs from 1 minute of PA fluoroscopy performed in the newborn and five-year old phantoms. For both phantoms identical imaging conditions were used for these baseline assessments with the exception of the magnification settings where one step higher camera magnification was used in the newborn (approximating normal imaging). Both air kerma and DAP were substantially lower in the newborn when compared to the five-year old (air kerma 1.6 mGy versus 4.3 mGy and DAP 63 mGy·cm² versus 238 mGy·cm² for the newborn and five-year old respectively). However, effective doses were closer (0.36 mSv versus 0.41 mSv for the newborn and five-year old respectively) reflecting greater tissue attenuation in the five-year old. As anticipated, organs in the imaging field-of-view, including lungs, esophagus, bone and breasts, received the majority of the dose.

Imaging parameters

Table II summarizes the radiation dose settings, air kerma and Monte Carlo estimated effective dose across the spectrum of imaging parameters varied, in the newborn- and five-year old phantoms. Camera magnification, collimation and SID all had a substantial effect on radiation dose. In the newborn doses per minute of PA fluoroscopy varied by more than four-fold, ranging from 0.14 mSv to 0.58 mSv depending on the imaging parameters. Similarly doses in the five-year ranged widely from 0.22 mSv to 0.79 mSv. The effects are summarized in Figure I.

System parameters

Table III summarizes various system modifications and the impact on dose. For an equivalent time period cineangiographic doses were 5.8-fold and 6.3-fold higher than fluoroscopy doses in the newborn and five-year old respectively. For imaging in the neonate, we tested the impact of beam parameters optimized for a school-aged child (35-55 lbs) rather than a < 10 lb infant. These settings resulted in an increase of 3.0 in kvp (from 66 kvp to 69 kvp) and 1.0 in mA (from 2.3 mA to 3.3 mA) and this translated to an 83% increase in effective dose.

In the neonate and five-year-old, removal of the anti-scatter grid reduced effective dose for PA imaging by 31% and 46% respectively. Grid removal also reduced effective dose for lateral fluoroscopy in the newborn (-31%) but marginally increased effective dose (+9%) in the five-year old, reflecting the increased potential for scatter from the lateral projection in the larger sized phantom.

As expected, fluoroscopy and cineangiography pulse and frame rates reduced doses proportionate to the reduction in pulses/frame rates.

Optimized versus sub-optimal imaging and lifetime attributable cancer risk

Table IV demonstrates the combined impact of several imaging parameters on overall radiation dose and Figure II demonstrates the camera position and images for these scenarios in the phantoms. In the “sub-optimal” newborn scenario imaging was performed with 6” magnification, with no collimation and the receptor raised by 20cm. With these parameters optimized for dose reduction (8” magnification with collimation to the imaging field of view and a maximally lowered receptor), dose was reduced almost three-fold from 0.74 mSv to 0.27 mSv per minute of fluoroscopy (Figure II). This dose was further lowered to 0.14 mSv per minute with removal of the anti-scatter grid and lowering of the pulse rate from 15pps to 10pps. A similar scenario is demonstrated for the five-year-old phantom with a four-fold dose reduction from 0.96 mSv to 0.24 mSv per minute of fluoroscopy with optimization of the imaging parameters, and further reduction in dose to 0.11 mSv per minute with addition of the technical modifications (anti-scatter grid removal and a pulse rate of 10pps).

To provide clinical perspective and to quantify the interaction between imaging approach and age / gender, we then calculated the impact of suboptimal versus optimized PA imaging on LAR of cancer and of fatal cancer for procedures with varying fluoroscopy times (Figure III, Table V). For imaging parameters optimized for dose reduction, the lifetime risk was

relatively low -- an estimated 4 to 14 cancer cases per 10,000 exposed to 10 minutes of fluoroscopy, depending on age at exposure and gender. However when using sub-optimal imaging, estimated cancer risk increased substantially. For example, estimated LAR of cancer after 30-minutes of PA fluoroscopy using optimized versus sub-optimal imaging respectively was: 0.42% versus 1.23% (newborn female), 0.20% vs 0.53% (newborn male), 0.35% versus 1.27% (5-year-old female) and 0.12% vs 0.50% (5-year-old male). Note that these estimates are only based on modifications in imaging parameters. Technical modifications (anti-scatter grid removal and lowering of pulse rates to 10 pps) reduce risk further (Table V).

Correlation between DAP / air kerma and effective dose

Figure IV plots DAP and air kerma values versus effective dose. Correlation between air kerma and DAP with effective dose was excellent when evaluating only doses obtained in the newborn ($r=0.91$, $p<0.01$ for air kerma and $r=0.89$, $p<0.01$ for DAP). However correlation was less optimal in the five-year old (r values of 0.54 to 0.72) and when the fluoroscopy data from both phantoms were combined (r values of 0.51 to 0.71). There were also several seemingly paradoxical incidences when comparing the dose parameters. For example a DAP of 257 mGy·cm² in the five year old was associated with an effective dose of 0.14 mSv while a much lower DAP of 94 mGy·cm² in the newborn was associated with a much higher effective dose of 0.74 mSv.

Discussion

To our knowledge, this is the first report to quantify the impact of these imaging and technical parameters on absorbed radiation dose during pediatric cardiac catheterization. Our dose estimates provide actionable information that can be used by pediatric interventional cardiologists to improve procedural safety. Moreover our risk estimates demonstrate the substantial impact that optimizing imaging to reduce radiation dose can have on lifetime cancer risk for children undergoing cardiac catheterization.

Image optimization to reduce radiation dose has been highlighted by professional societies including the American College of Cardiology and the Society for Cardiovascular Angiography and Interventions as a major quality improvement objective for the pediatric interventional cardiology community(15,16) With respect to standard optimization techniques (e.g. collimation, image-receptor height and camera magnification), our data are all consistent with prior studies in adults.(8,9) However, the relative impact has not been previously quantified in children and it is notable that there was variability depending on the age and weight of the phantoms. Our pediatric-specific data provide valuable perspective and can motivate interventionalists to maximally optimize their imaging approach.

Beyond standard operator-dependent optimization techniques, an important finding from our study was the relative effect of “infant” beam parameters (kVp and milliamperage optimized for weight < 10lbs). Previous analyses have demonstrated the importance of pediatric-specific fluoroscopy settings;(19) using adult beam parameters in a young child can increase dose by more than 50-fold when compared to pediatric beam parameters.(20) Our data demonstrate that even using “toddler” settings in an infant is suboptimal, resulting in an

increase in effective dose of >80%. Ideally fluoroscopy systems being used for pediatric patients should include a wide range of settings to accommodate the variability in age, weight and body habitus of children undergoing cardiac catheterization and providers should be particularly attentive to the use of optimal settings specific to the age and body habitus of the child.

A sometimes debated measure is the use of anti-scatter grids in young children. These grids, located on the receptor, improve image quality by screening out scatter radiation. However anti-scatter grids cause autoexposure controls to increase the output dose. In larger patients this compromise may be worthwhile because scatter radiation contributes to poor image quality; by screening out scatter, lower dose settings can be used. However in younger children scatter radiation is less significant and image degradation is relatively minimal. Ubeda et al. measured the effect of an anti-scatter grid on image quality and air kerma in pediatric patients using a Siemen Axiom fluoroscopy system (17:1 grid ratio, 70 lines per cm and 100cm focal distance).(21) They recommended routine removal of anti-scatter grids in neonates and infants (something that can be easily done on most modern fluoroscopy systems) but noted more significant image degradation in children of approximately five-years and older (>19kg). Our data are consistent with their analysis, demonstrating Bucky factors (the ratio of air kerma with and without the antiscatter grid) of 1.5 and 1.8 for PA fluoroscopy in the newborn and five-year-old phantoms respectively. Our effective dose reductions of 46% and 31% for PA fluoroscopy in the two phantoms indicate that removal of the anti-scatter grid will significantly lower dose and related risk. However, it is interesting that the effect was less notable (actually marginally increased for the five-year old) in the lateral projection. This presumably reflects increased scatter associated with the greater thorax dimensions from side to side versus front to back imaging. In our opinion anti-scatter grids should be routinely removed in younger children. At older ages (weights > 15-20kg) the dose reductions are potentially meaningful but proceduralists will need to weigh the impact on image quality.

Another notable finding from this analysis is the association between the surface exposure dose estimates (air kerma and DAP) and effective dose. DAP and air kerma are important measures of irradiation output by the system but they have limitations when estimating the actual dose to organs because they fail to account for tissue attenuation of the X-ray beam and other physical conditions. Fluoroscopy auto-exposure controls will automatically increase the radiation dose for a larger patient to maintain image quality however dose penetration will be relatively lower due to beam attenuation. Moreover different organs have different radiation sensitivity and therefore it is important to understand the relative dose to differing organs. For these reasons effective dose is useful, representing the sum of organ absorbed doses multiplied by a weighting factor that accounts for organ sensitivity.(1,2,13) Our data demonstrate the limitations of DAP/air kerma as estimates of organ specific doses. For example, DAP was four-fold higher in the 5-year old phantom compared to the newborn yet the effective dose was almost identical, reflecting the increased tissue attenuation in the larger phantom. There was also relatively poor correlation between air kerma/DAP and effective dose when comparing across age ranges (i.e. when combining the newborn and five year old data). We would anticipate that correlation would be even worse when comparing across a wider age and body habitus range than the 0 to five year range in this analysis.

There is also the potential for misrepresenting risks when relying upon DAP or air kerma. This is demonstrated by the frequent seemingly paradoxical relationships where surface exposure was much higher in the larger versus smaller phantom but effective doses were actually lower. Further study is needed to better understand the complex relationship between surface dose and absorbed dose across the wide spectrum of pediatric patients, both in terms of age and body habitus (e.g. impact of obesity).

There are important limitations to our analysis. First imaging was performed on a single fluoroscopy system. Different systems may behave differently and/or have lower or higher absolute doses for a given imaging approach. However the relative dose reductions are the most important finding from our analysis and these would be expected to persist even if the absolute estimates may vary. A second limitation is that Monte Carlo simulations represent mathematical estimates of organ dose. There may be some error in these estimates. However any errors should be systematic and our primary objective was to estimate variability in imaging parameters that were individually manipulated for each imaging protocol. In these scenarios Monte Carlo estimates provide an accurate means for assessing relative dose reductions for each of the various imaging protocols. We were also limited by the availability of only a newborn and five-year old phantom. Radiation doses may vary with body habitus even in this relatively narrow age range. Third it is important to recognize that dose reduction is only one half of the imaging equation. Image quality is equally as important to patient care and safety. Many of the dose optimization parameters would be expected to improve image quality (e.g. collimation, lowered camera, arms out of the imaging field-of-view) however others may decrease image quality (frame/pulse rates, anti-scatter grid removal, decreased camera magnification). Our data are intended to provide perspective on the magnitude of impact on radiation dose. However there may be times when higher doses are necessary to optimize procedural safety and/or efficacy. Finally there are well recognized limitations in the BEIR VII cancer risk estimates. These estimates should not be applied to individual patients and do not accurately reflect risk to patients with shortened life expectancy. However our use of the BEIR VII risk estimates is consistent with their intended use to evaluate risk across procedural approaches in populations of patients. Despite the known limitations of these risk models, they are widely published as there are benefits to estimating cancer LAR including the ability to impart to providers the direct clinical applicability of image optimization, and the fact that effective dose does not adequately convey the differing risk to patients of differing ages and genders. Ultimately our cancer LAR estimates are intended to provide clinical perspective regarding the potential for increased risk when using a suboptimal imaging approach.

In conclusion we demonstrate the substantial impact of various imaging parameters and fluoroscopy settings on radiation dose and associated risk from pediatric cardiac catheterization. Image optimization can reduce radiation dose and associated risk by several fold, emphasizing the importance of attention to detail to improve procedural safety

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Figure I.
 Variability in effective dose with manipulation of various imaging parameters in the newborn and five-year old phantoms. Dose estimates are for 1 minute of fluoroscopy exposure.

Figure II.

Impact of optimized imaging on effective dose in the newborn (A) and five-year old (B) phantoms. From left to right the image sequences represent sub-optimal, intermediate and optimized imaging parameters. The final image represents optimized imaging parameters + technical modifications (removal of the anti-scatter grid and reduction in the pulse rate from 15 to 10 pps). Dose estimates are for 1 minute of PA fluoroscopy and represent mSv $\pm$ error %.

Figure III.

Impact of image optimization on lifetime attributable risk (LAR) of cancer. Risk estimates are based on minutes of PA fluoroscopy exposure and do not represent a realistic clinical scenario. They are intended only to demonstrate the potential clinical impact of variations in imaging approach.

Figure IV.
Correlation between effective dose and air kerma / DAP

Table I

Doses to cancer susceptible organs from 1 minute of PA fluoroscopy exposure

	Newborn Fluoro mGy (% error)	5-yo Fluoro mGy (% error)
Lungs	1.24 (1.1)	1.69 (1.0)
Esophagus	0.81 (6.4)	0.96 (4.1)
Bone surface	0.71 (0.7)	0.71 (0.7)
Breasts	0.55 (32.7)	0.65 (17.7)
Liver	0.31 (2.0)	0.17 (2.3)
Stomach	0.23 (6.2)	0.10 (6.6)
Active bone marrow	0.23 (0.7)	0.26 (0.7)
Skin	0.15 (1.9)	0.14 (2.1)
Thyroid	0.10 (16.9)	0.07 (27.9)
Salivary glands	0.05 (16.1)	0.04 (11.8)
Colon	0.03 (7.8)	0.12 (12.6)
Ovaries	0.02 (65.8)	0.03 (99.9)
Uterus	0.02 (16.6)	0.01 (83.1)
Brain	0.01 (5.9)	0.01 (8.2)
Bladder	-	-
Testicles	-	-
Effective dose (mSv)	0.36 (6.0)	0.41 (3.5)

Imaging performed with 1" inch periphery collimation, 93cm source to image distance (SID), 5cm phantom-to-receptor distance, low contrast fluoroscopy at 15 frames per second with filtration (1mm aluminum + 0.4mm copper). 6" magnification was used for the newborn and 8" for the 5-year-old.

Table II

Effect of image parameters on radiation dose

Phantom	C/G-arm	Projection	SID (cm)	Camera magnification (inches)	Collimation (inches)	KV / mA	Kerma (mGy/60s)	Effective dose (mSv/60s) ± Error	from standard view
Newborn									
Standard image	C	PA	93	6"	1"	66 / 2.3	1.60	0.36 ± 0.02	-
8" magnification	C	PA	93	8"	To 6" FOV	73 / 4.4	0.64	0.16 ± 0.03	-56%
10" magnification	C	PA	93	10"	To 6" FOV	70 / 3.4	0.60	0.14 ± 0.02	-61%
No collimation	C	PA	93	6"	0	66 / 2.3	1.75	0.62 ± 0.04	+72%
2" collimation	C	PA	93	6"	2"	66 / 2.4	1.63	0.28 ± 0.02	-22%
Camera raised 10cm	C	PA	103	6"	1"	67 / 2.7	1.97	0.53 ± 0.04	+47%
Camera raised 20cm	C	PA	113	6"	1"	68 / 3.0	2.42	0.58 ± 0.03	+61%
Straight lateral	G	Lateral	112	6"	1"	66 / 2.2	1.37	0.28 ± 0.02	-
Straight lateral + arms	G	Lateral	112	6"	1"	71 / 3.6	3.48	0.62 ± 0.03	+121%*
Five-year old									
Standard image	C	PA	93	8"	1"	72 / 4.1	4.13	0.41 ± 0.01	-
10" magnification	C	PA	93	10"	To 8" FOV	70 / 3.1	2.63	0.22 ± 0.01	-46%
6" magnification	C	PA	93	6"	To 8" FOV	76 / 4.4	7.07	0.73 ± 0.02	+78%
No collimation	C	PA	93	8"	0	74 / 4.3	5.03	0.79 ± 0.03	+93%
2" collimation	C	PA	93	8"	2"	74 / 4.4	4.86	0.28 ± 0.01	-32%
Camera raised 10cm	C	PA	103	8"	1"	74 / 4.3	4.77	0.52 ± 0.02	+27%
Camera raised 20cm	C	PA	113	8"	1"	75 / 4.8	5.60	0.65 ± 0.03	+59%
Straight lateral	G	Lateral	112	8"	1"	68 / 2.7	3.27	0.58 ± 0.03	-

Table III

Effect of system parameters on radiation dose

Phantom	C/G-arm	Projection	SID (cm)	Camera magnification (inches)	Collimation (inches)	KV	mA	Kerma (mGy/60s)	Effective dose (mSv/60s) $\pm$ Error %	from standard view
Newborn										
Standard image PA	C	PA	93	6"	1"	66	2.3	1.60	0.36 $\pm$ 0.02	-
Standard image lateral	G	Lateral	112	6"	1"	66	2.2	1.37	0.28 $\pm$ 0.02	-
Child beam settings	C	PA	93	6"	1"	69	3.3	2.94	0.66 $\pm$ 0.04	+83%
10 pps fluoroscopy	C	PA	93	6"	1"	66	2.3	1.1	0.24 $\pm$ 0.02	-33%
Cineangiography 15fps	C	PA	93	6"	1"	69	121 (4ms)	4.2	1.1 $\pm$ 0.09	-
Cineangiography 30fps	C	PA	93	6"	1"	69	121 (4ms)	8.4	2.1 $\pm$ 0.17	+91%
Grid removed	C	PA	93	6"	1"	63	1.7	1.1	0.25 $\pm$ 0.02	-31%
Grid removed lateral	G	Lateral	93	6"	1"	63	1.7	0.75	0.23 $\pm$ 0.02	-22%
Five-year old										
Standard image PA	C	PA	93	8"	1"	72	4.1	4.13	0.41 $\pm$ 0.01	-
Standard image lateral	G	Lateral	112	8"	1"	68	2.7	3.27	0.58 $\pm$ 0.03	-
10 pps fluoroscopy	C	PA	93	8"	1"	72	4.1	2.75	0.27 $\pm$ 0.01	-33%
Cineangiography 30fps	C	PA	93	8"	1"	65	336 (4ms)	13.88	2.6 $\pm$ 0.08	-
Cineangiography 15fps	C	PA	93	8"	1"	65	336 (4ms)	6.95	1.3 $\pm$ 0.04	-50%
Grid removed	C	PA	93	8"	1"	69	3.1	2.36	0.22 $\pm$ 0.01	-46%
Grid removed lateral	G	Lateral	112	8"	1"	67	2.7	3.57	0.63 $\pm$ 0.03	+9%

Dose estimates for 1 minute of fluoroscopy or cineangiographic exposure performed at 15pps (fluoroscopy) and 15fps with 0.4sec pulse width (cineangiography) unless otherwise stated. C and G-arm correspond to the PA and lateral camera arms respectively, PA-postero-anterior; SID-source-to-image distance; pps and fps represents pulses and frames per second respectively; Grid represents the anti-scatter grid

Table IV

Effect of optimization of imaging and technical parameters on radiation dose

	SID (cm)	Camera magnification (inches)	Collimation (cm)	KV	mA	Kerma (mGy/60s)	Effective dose (mSv/60s) ± Error %
Newborn							
Optimized image, no grid, 10pps	93	8"	2"	63	1.5	0.55	0.14 ± 0.01
Optimized image	93	8"	2"	64	2.0	1.20	0.27 ± 0.01
Intermediate image	100	6"	1"	67	2.6	1.88	0.45 ± 0.02
Suboptimal image	110	6"	0	68	2.9	2.23	0.74 ± 0.05
Five-year old							
Optimized image, no grid, 10pps	93	10"	2"	69	2.2	1.11	0.11 ± 0.01
Optimized image	93	10"	2"	69	3.2	2.66	0.24 ± 0.01
Intermediate image	100	8"	1"	74	4.3	4.71	0.50 ± 0.01
Suboptimal image	110	8"	0	75	4.7	5.66	0.96 ± 0.03

Dose estimates for 1 minute of fluoroscopy exposure (15pps) unless otherwise stated. PA-postero-anterior; SID-source-to-image distance; pps and fps represents pulses and frames per second respectively; Grid represents the anti-scatter grid

Table V

Lifetime attributable risk of cancer and fatal cancer by imaging approach

	Cancer LAR (cases per 10,000 exposed)			Fatal Cancer LAR (cases per 10,000 exposed)		
	10min	30min	60min	10min	30min	60min
Newborn female						
Optimized image, no grid, 10pps	9.2	27.6	55.2	4.3	13.0	26.0
Optimized image	14.1	42.3	84.7	8.2	24.6	49.1
Intermediate image	24.9	74.6	149.2	13.7	41.0	81.9
Suboptimal image	41.0	122.9	245.8	20.3	60.8	121.6
Newborn male						
Optimized image, no grid, 10pps	2.9	8.8	17.6	1.9	5.8	11.7
Optimized image	6.7	20.1	40.1	4.3	13.0	26.0
Intermediate image	10.6	31.7	63.4	6.9	20.8	41.5
Suboptimal image	17.5	52.5	104.9	10.4	31.3	62.6
Five-year old female						
Optimized image, no grid, 10pps	5.4	16.3	32.5	3.2	9.5	19.0
Optimized image	11.8	35.3	70.6	6.8	20.3	40.5
Intermediate image	23.1	69.4	138.9	14.0	41.9	83.8
Suboptimal image	42.3	127.0	254.1	26.2	78.6	157.2
Five-year old male						
Optimized image, no grid, 10pps	1.9	5.6	11.1	1.5	4.4	8.8
Optimized image	4.0	12.1	24.1	3.1	9.4	18.8
Intermediate image	8.4	25.2	50.3	7.6	22.9	45.7
Suboptimal image	16.8	50.3	100.7	13.0	38.9	77.7

Cancer risk estimates for PA fluoroscopy exposure, grid refers to the antiscatter grid, pps-pulse per second