Volume 11 - Issue 2, 2011 - Cover Story: A Primer on Radiation Protection: Patient & Personnel Safety in Focus

X-Ray Beam Optimisation for Paediatric Interventional Cardiac Imaging

In the cardiac catheterisation lab, image sequences of the heart are captured by a dynamic x-ray imaging system to allow real time visualisation of catheter movement within the vessels. An iodine-based contrast medium is often utilised to allow clear visualisation of blood flow through the arteries, ventricles, and valves of the heart. Cardiac image sequences must be captured with high spatial and temporal resolution to identify occlusions and other perturbations of blood flow within the heart against the visible background anatomy. Such procedures are used to diagnose and treat congenital heart disease in children; they are becoming increasingly complex and frequent. Echocardiography and Doppler ultrasound may also be utilised to obtain diagnostic information without the use of ionising radiation. However, real-time x-ray imaging is essential in order to perform these minimally-invasive interventional cardiac procedures.

The ALARA concept (keep radiation dose As Low As Reasonably Achievable) is paramount for all x-ray imaging modalities and patients, but it is especially important for paediatric patients with congenital heart disease. The majority of adult patients undergoing interventional cardiac procedures are at least middle aged, suffering from age or lifestyle related heart problems. Paediatric patients, on the other hand, usually have a congenital disease which requires multiple, lengthy interventional procedures over the course of their childhood.

Children are still growing, so their cells are rapidly dividing, making them more prone to DNA damage from radiation than adults. This higher radiosensitivity is demonstrated in figure 1, where a Sievert (Sv) is a unit of measurement for radiation dose. Combined with the longer mean life expectancy of children, this makes them vulnerable to long term stochastic effects of biological tissue damage from radiation such as long term chromosomal damage. In addition, paediatric anatomy shows that younger patients' vital organs are in closer proximity to each other than those of older patients. This closer proximity results in a higher radiation dose to vital organs near the area of interest, in this case the heart.

In 1978, a published study of blood samples before and after interventional cardiac procedures of infants and children demonstrated post-procedure chromosome damage, suggesting long-term follow-up. Now, attention has gradually been brought to this matter, with Step Lightly, an extension of the Image Gently Campaign. Its message is to "child size" x-ray exam protocols, to step lightly on the pedal, and to consider other modalities rather than radiation based imaging. Participants of Step Lightly are predominantly in U.S. and Canada, but the campaign now has links with the International Atomic Energy Agency (IAEA) based in Vienna, Austria.

Dose Measurements

The literature often points to a specific solution in order to keep paediatric dose ALARA - evaluate radiation dose, implement dose reduction techniques, and monitor dose. It may also be necessary to re-evaluate equipment or xray techniques used. In terms of the first stage, dose surveys for paediatric interventional x-ray procedures are being performed by medical physicists more in recent years, with results published in peer-reviewed journals "as a first step towards optimisation". Results vary in several capacities, mainly the type of dose measurements used. Some dose surveys retroactively collect procedure dose values, which had been reported by the x-ray system at the end of each procedure. Others use calculations based on x-ray parameters or precise, in-vivo dosimetry methods similar to those used in high energy radiotherapy procedures.

Published dose surveys often differ in methods used to quantify radiation dose. Dose area product (DAP) is reported by modern x-ray systems, measured with an ionisation chamber built into the x-ray system. Skin dose is the patient entrance surface dose (ESD) including backscattered x-rays; it is the best risk indicator for erythema. Skin erythema is a deterministic effect of radiation, so there is a threshold dose value which determines its likelihood; this is a concern for adult cardiac xray imaging, where high beam energies are required to penetrate thick chests. At times, the patient entrance air kerma (ESD without backscatter) is documented. ESD and kerma may be calculated by equipment software, or measured by a physicist.

All of these dose measurements have the unit Gray (Gy). DAP is the most commonly reported dose measurement; it is useful for inter and intra-departmental comparisons of procedures dose, but without further calculations, it does not on its own directly provide information about deterministic or stochastic risks of radiation.

Effective dose, which has the unit Sievert (Sv), is an estimate of the stochastic risks of radiation. It includes different radiosensitivities of various biological tissues and age groups by implementing weighting factors in a calculation. Effective dose may not be directly measured; one of the above measurements must be converted to effective dose using established conversion factors. If sophisticated software such as PCXMC (STUK, Finland) is used to calculate effective dose, an organ dose breakdown is provided.

It is also worth noting that organ weighting factors are changed every few years to reflect new knowledge gained; this knowledge is built from examining atomic bomb survivors for long term effects of radiation. Effective dose is often outside the scope of published catheterisation lab dose surveys. However, it is the most important dose measurement concerning long term effects on paediatric patients with congenital heart disease.

Models Indicate Greater Understanding

Recent literature indicates an increasingly developing understanding of stochastic risks of radiation. Biologically motivated mathematical models have been built and Monte Carlo simulations performed to understand mechanisms of radiation-induced carcinogenesis. In one study, data from Biological Effects of Ionising Radiation (BEIR) VII helped determine the lifetime attributable risk of cancer associated with estimated radiation dose in children with complex congenital heart disease. A micronucleus assay was performed before and two hours after the interventional procedure; this was used as a biomarker of chromosomal damage and intermediate end point of carcinogenesis. Results demonstrated a need for radiation dose reduction in these children.

In addition to the various methods of quantifying radiation dose, there are a variety of dynamic x-ray imaging systems in use – image intensifier based, digital flat panel detector based, bi-plane, single plane, to name a few. Not only the x-ray detectors and system geometry differ, but x-ray tubes built over the last few decades vary greatly in power. Different manufacturers implement differing settings for paediatric imaging, some more child-specific than others. Some hospital departments have made alterations to x-ray systems to make the default settings more child-specific.

Such differences are often world region dependent; some regions prioritise impressive image quality whereas others are extremely conscious of patient dose. Many published dose surveys have identified the need to establish paediatricspecific diagnostic reference levels for interventional cardiac procedures. This would allow for a consistent comparison between heart centres.

Balancing Image Quality with Dose

The well-known trade-off or balance between image quality and radiation dose that exists for all x-ray imaging makes it difficult to optimise image quality with radiation dose. For children, fast heart rates require faster acquisition rates of image frames. If the frame speed is reduced in order to reduce radiation dose, the temporal resolution of the image sequence drops. This adds to the existing trade-off between image quality and radiation dose per frame.

X-ray parameters and geometric settings used on a given imaging system for a given diagnostic task differ in adult cardiac imaging from those used over the range of paediatric sizes. Smaller patients produce fewer scattered x-rays; they require less radiation in order to achieve suitable clinical image quality. The image quality to patient dose balance is hence different for paediatric cardiac x-ray imaging than for adults due to the broad range of smaller body sizes. There is a need for paediatric-specific optimisation of x-ray parameters.

Good practice in radiology will result in dose reduction, as implemented by radiography staff. Depending on staff training and the imaging system used, some examples are x-ray beam collimation, use of pulsed x-rays and of last image hold, reduction of frame rate when feasible, and removal of anti-scatter grid for younger children. When optimising a cardiac catheterisation lab for paediatrics, these are the first steps in dose reduction. Good radiological practice should always be exercised.

Optimising X-Ray Beam Energy

For further optimisation, imaging systems utilise x-ray beam spectral filtration such as copper, in varying amounts. Copper reduces ESD whilst causing a slight reduction in image quality. A collection of published paediatric optimisation studies demonstrates no consensus regarding the correct amount of copper to use. Many optimisation studies also suggest alteration of x-ray peak tube voltage; some recommend raising it while others recommend lowering it. The peak tube voltage and spectral beam filtration together define the x-ray beam energy. There is a complex relationship between beam energy and patient size, and their effects on both image quality and dose. Examining both peak tube voltage and spectral beam filtration is necessary in order to optimise x-ray beam energy for patient size, to achieve the best image quality to dose balance for a particular patient size.

X-ray tube voltage is set by the automatic dose rate control (ADRC) of the imaging equipment, in response to the amount of copper spectral filtration present. Radiographic factors are automatically selected by the ADRC when the foot pedal is engaged, for fast easy use by clinicians. This closed loop operating mechanism makes it impossible for physicists to investigate the optimisation effects of peak tube voltage and of copper beam filtration independently.

The Leeds X-ray Imaging Research Group (The University of Leeds, UK) conducted an experiment in which the ADRC was surpassed to explore optimal x-ray beam energy for three different paediatric patient sizes. Peak tube voltage and copper beam spectra were varied in a controlled manner to observe optimisation effects of x-ray beam energy with respect to imaging iodine. The study was conducted on a flat panel imaging system, but due to the nature of the investigation, results were system-independent, and addressed general x-ray principles.

Image sequences of 8.5, 12, and 16 cm thick phantoms were used to approximate x-ray attenuation of typical paediatric patient chest sizes. Peak tube voltage, tube current and x-ray pulse duration were set manually by over-riding the system's ADRC mechanisms. Image contrast to noise ratio (CNR) and effective dose were determined to calculate the optimisation figure of merit (FOM), CNR2/effective dose. Full details of the experiment can be found in Gislason et al. (Medical Physics, 2010). Results are shown in figures 2 – 4; it is clear that for thicker copper filtration, lower peak tube voltage was favoured. Regardless of the filtration, lower peak tube voltage was generally favoured, more so for thinner phantoms. Where higher peak tube voltage was used, thinner (or no) copper filtration was favoured. The study concluded that in terms of beam energy, for iodine contrast agent based xray imaging, the image quality to effective dose balance can be improved by adding 0.25-0.4 mm copper filtration to the x-ray beam while maintaining a peak tube voltage of 50 kVp, depending on patient size. These results are in agreement with a Monte Carlo simulation study completed in 1999.

In addition to good radiological practice, for optimisation of image quality to dose in paediatric cardiac x-ray imaging, the x-ray beam energy should be adjusted for patient size. Actual peak tube voltage and spectral filtration used will depend on the x-ray tube and its inherent limitations. If this concept is not already implemented, for some imaging systems, adjustment may involve re-programming ADRC settings, which may require the hospital medical physicist and/or field service engineer. Every extra effort made will help reduce the chance of paediatric patients with congenital heart disease developing radiation-induced cancer later in life.

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