Radiation Exposure in Imaging of Suspected Child Abuse: Benefits versus Risks

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Recent articles on child abuse in this journal discussed the value of ordering a skeletal survey in children age 24-36 months and the need for a computed tomography (CT) of the head in children less than 2 years with an isolated single nonmetaphyseal long bone fracture.[1-3] The benefits of these and other imaging studies are not merely in the number of positive tests. Negative results can be extremely important. However, both radiography and CT use ionizing radiation (X-rays). Determining the risks of radiation exposure from medical imaging is not straight forward. Radiation doses vary considerably depending on the modality, the type of study, the number of images, and the techniques used. Understanding the ability of an imaging examination (ie, CT vs magnetic resonance [MR] imaging) to accurately identify the pathology is crucial in test selection.

Basic Principles

1. Imaging tests should be ordered based on the history and physical examination and a well thought out differential diagnosis.
2. Clinical imaging guidelines serve as the foundation of what to begin with. Guidelines usually start with the less invasive test that has a high sensitivity and reasonable specificity. Follow-up imaging (problem solving tests) should be ordered based on the individual patient's unanswered clinical and imaging questions.
3. The risks for any imaging test include (if applicable) the effects of ionizing radiation and complications of sedation or general anesthesia.[4] Importantly, consideration must be given to the risks of not doing the test and missing a diagnosis.
4. Children are more sensitive to the effects of radiation exposure.[5,6] Therefore, the as low as reasonably achievable (ALARA) principle dose of radiation, while obtaining diagnostic images, must be adhered to by the ordering physician in test selection and by the imager through protocol design and in supervision of technical staff in performing the examination.
5. All imaging facilities are not the same.[7,8] Pediatric centers use standard protocols that have been determined by national guidelines and concern for radiation.[9] Imaging at pediatric-focused facilities with access to subspecialty consultation on what images to acquire in any nonroutine cases adds greatly to the appropriate care of children.
6. "Image Gently" (www.imagegently.org) is a source of information about ionizing radiation awareness for parents and healthcare practitioner. The Alliance for Radiation Safety in Pediatric Imaging was formed in 2007 and consists of 84 leading medical societies, agencies, and regulatory groups. This alliance created "Image Gently" to "impact patient care and change practice through an educational and awareness campaign."[10] The means of achieving diagnostic images at a properly managed radiation dose is a sentinel concept of the campaign. This focus, together with emphasis on proper medical indications for doing an imaging examination (meeting appropriateness criteria), form the cornerstones of intelligent test selection.

The ALARA acronym is used to denote properly managed radiation dose by the "Image Gently" campaign. The original use of ALARA was limited to ionizing radiation received by healthcare workers (occupational exposure).

Risks of Exposure to Ionizing Radiation

All modes of imaging within diagnostic radiology departments subject the patient to penetrating beams of energy carried by radio waves (MR), mechanical waves (ultrasound), γ-rays (nuclear medicine), or X-rays. The radio waves and mechanical waves of MR and ultrasound, at the energy levels used in diagnostic tests, are believed to be risk free. However, the X- and γ -rays are forms of ionizing radiation; these rays ionize tissue molecules as they travel through the body, which if concentrated, can lead to biological damage. As the X or γ radiation beam deposits energy in the superficial layers of the patient's tissues, less energy is carried by the beam resulting in less dose to tissues at a greater depth in the body relative to the entrance plane of the beam (attenuation). This explains why one must designate where

ALARA	As low as reasonably achievable
CT	Computed tomography
MR	Magnetic resonance

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K.S. provides paid consulting services to Philips Healthcare (Best, The Netherlands) upon request. The other authors declare no conflicts of interest.

http://dx.doi.org/10.1016/j.jpeds.2015.07.064

any specified dose is located—skin entrance, midline, exit plane, or specific organ location.

Radiation Metrics

A basic understanding of radiation dose metrics[5,6,11] is necessary to aid the discussion of the implications of ionizing radiation in imaging. Absorbed dose indicates that energy is deposited microscopically in the tissue of the body as X- or γ-rays pass through. Absorbed doses are typically not measured; they are estimated from measurements of the amount of radiation arriving at the entrance skin plane of the patient (air Kerma). The unit of the absorbed dose is the gray (Gy) or milliGy (mGy). Historically, absorbed dose was expressed in rads or mrads (1 mGy = 100 mrad).

Ionizing radiation dose may also be expressed as equivalent dose. Equivalent dose is used to report occupational radiation doses. For all diagnostic tests conducted in radiology, which use X- or γ-ray, the absorbed dose and equivalent dose (typically at the entrance plane of the patient's body) are equal. However, unlike absorbed dose, the unit of equivalent dose is the Sievert (Sv). The equivalent dose is usually expressed in milliSieverts (mSv). The historical unit is the rem (100 rem = 1 Sv).

Ionizing radiation dose is sometimes expressed as effective dose, which must not be confused with equivalent dose, even though both dose indices use the same units, Sv or mSv. Effective dose is a dose to the whole body and defined only for a population, and equivalent dose is a dose to a subset of the whole body of an individual patient. When a dose is expressed in Sieverts, one must carefully identify which dose index is being used—effective or equivalent. If an effective dose is assumed to be an equivalent dose, the dose to directly irradiated organs and their potential risk will be significantly underestimated (by a factor more than 10).

It is good to use a reference point to understand metrics. For background radiation the effective dose is approximately 0.01 mSv per day and 3-3.5 mSv per year.[11] Radiation doses from diagnostic studies vary from modality to modality and type of examination from 0.03 mGy to over 50 mGy (**Table**). Most of the absorbed doses in the **Table** are expressed as a range because the skin dose to the patient varies by thickness of body part irradiated and length of the path of the X-ray through the body.

Table. Relative radiation dose of some common examinations in a 2-year-old child

Examination	Dose range (mGy)	Where measured
Chest 1 view	0.03-0.08	Skin entrance
Abdomen 1 view	0.2-0.3	Skin entrance
Humerus 1 view	0.08	Skin entrance
Femur 1 view	0.12	Skin entrance
Spine thoracolumbar frontal view	0.34	Skin entrance
Head CT, standard†	20-25	Skin entrance*
Head CT, reduced dose for skull‡	4-5	Skin entrance*
Abdominal CT	4-8	Skin entrance*

3D, 3-dimensional; *CTDIvol*, CT dose index volume.
*Skin dose is approximately 10% greater than the dose reported as CTDIvol. The CTDIvol is the dose reported on the scanner and is measured by a phantom simulating the center portion of the body region scanned.
†The first head CT technique is for evaluation of the brain and is a higher radiation dose procedure. It is not a helical scan but individual axial slices.
‡The second head CT technique is a lower radiation dose helical scan designed only for bone detail and requiring much less radiation. This is a volumetric or 3D-examination. When using the higher radiation dose head CT technique, images can also be reconstructed with 3D volume rendering to evaluate the skull with no additional radiation exposure.

Inherent Risks from Medical Radiation Doses

Effects from radiation exposure may be either deterministic (tissue reactions) or stochastic.[11] Deterministic effects (tissue reactions) have a threshold below which the effect does not occur. Once the threshold is crossed, the severity of the injury is typically proportional to the radiation dose. These include cataracts, skin burns, epilation, and more serious forms of skin damage. The doses required to cause skin burns are over 2 Gy, substantially greater than the doses incurred in most diagnostic tests.

Stochastic effects, carcinogenesis, occur randomly by chance. Energy transferred to a cell (absorbed dose) may alter the cell's DNA and cause mutations. The number of cells with mutations increase progressively from present to future generations over 10-30 years at which time malignancy may manifest. The National Council on Radiation Protection and Measurements tried but failed in 2 extensive studies (1993 and 2001) to identify a threshold below which no carcinogenic effect occurred.[12,13] This is modeled by the linear no-threshold concept of radiation safety.

Children are more vulnerable to carcinogenic effects of radiation than adults because of their higher cell duplication rates and their longer expected life span. It is well documented that the younger the age at the radiation exposure, the higher the risk of inducing cancer.[5]

The risk of tissue effects is cumulative. A patch of skin that has previously received large radiation doses will suffer a deterministic injury during a current procedure at a current dose less than 2 Gy. Stochastic effects, unlike tissue effects, are not cumulative. The risk to a patient from an 11th CT examination is identical to the risk of the patient's first 1st CT examination. A clinically justified additional radiation study should never be denied or discouraged because of the patient's radiation exposure history.

The scientific/medical community does not agree on the risk of cancer from radiation doses because of CT scans. Clinical studies with large cohorts of patients followed for over 40 years have suggested that a small individual risk of cancer exists from diagnostic imaging studies using ionizing radiation.[5,14-17] Theoretical extrapolations of additional malignancies because of increased radiation risk have ranged from 1/1000 in 2001 to 1/10 000 more recently because of dose reductions during CT.[18] However, a large clinical study published in 2015, for the first time identified that 32% of identified cancers during a 4- year follow-up period occurred in patients with cancer-predisposing factors other than ionizing radiation.[19] This study suggests that overestimates of risk may have occurred in previous studies because of