Comparative dose in pediatric radiology: uncertainty, estimates and ballparks

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There is an increasing need for all radiologists, particularly pediatric radiologists, to have a good working knowledge of the relative radiation dose of the examinations we perform or supervise. We must be capable of providing such information to our referring physicians, patients and their families, for internal quality-assurance purposes and in the future, perhaps to outside regulatory or advisory bodies.

In an ideal world, there would be a universally accepted common dose parameter applicable to all medical examinations involving ionizing radiation. That parameter would be derived with a user-friendly standard methodology that accounted for age and developmental variability and involved minimal extrapolations and assumptions. We do not have such a parameter. Currently, the most practicable common dose assessor is effective dose (ED). Defined by the ICRP and measured in milliSieverts (mSv), ED is the sum of the absorbed doses in all tissues and organs in the radiation field, each multiplied by a tissue-specific weighting factor. It provides an assessment of overall radiation detriment from a non-uniform dose distribution in terms of a uniform or whole-body exposure. The merits of ED are that it allows us to compare the relative dose impact of common radiographic, fluoroscopic, CT and nuclear medicine examinations, enables comparison to annual background radiation, and can be used together with risk models to provide a broad estimate of future excess malignancy risk.

However, there are reservations associated with its use in medical imaging, certainly when applied to an individual

patient. Calculation involves multiple levels of intrinsic uncertainties, extrapolations and error bars, generating an ED value that is a broader estimate than often appreciated. Expert assessment suggests that we should expect an uncertainty of $\pm 40\%$, whether using organ dose and weighting-factor methods; Monte Carlo simulations; or age-, region- and modality-specific conversion factor methods. Systematic and random components to error exist at each stage in calculation, and for all modalities. A few of the many potential contributors include dosimeter thresholds, accuracy, and placement; inter-observer variability in field of view specification with implication on partially included organs; whole-population based (not pediatric) weighting factors that are periodically updated with new epidemiological evidence; console-displayed CT dose parameters based on previously calculated standardized cylindrical phantom doses, the use of Monte Carlo or conversion factor data derived from older CT scanners, and uncertainties in models of radionuclide uptake, distribution and retention.

A decade ago, there was a paucity of available ED data for the practicing pediatric radiologist. Isolated publications addressed individual examinations, mostly radiographic and fluoroscopic studies, and there was some dose data from national surveys but rarely providing ED values. Although conversion coefficients were available, they were not widely appreciated beyond physics circles. There was almost no dose data for pediatric CT. Some ED values, when investigated, did not relate to children but to the more extensive, although still not comprehensive or collated, adult-based data. In the years since, publications involving organ dose measurement and ED estimation in pediatric imaging have escalated. The information available to all of us has significantly increased, although there is ongoing debate as to the merits of various approaches and a need to improve the methodology and inconsistencies that especially plague pediatric CT dosimetry.

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The compilation by Fred Mettler Jr of a summary of typical adult effective doses for more than 50 radiological procedures (Radiology 2008) was a milestone. It imparts an understanding of the relative dose of various examinations, which is as important as the absolute numerical data. At the time of writing, there was no equivalent pediatric summary. There are still significant gaps in the pediatric literature but we are accumulating an increasing bank of knowledge from which to provide information to our patients. Figure 1 shows some representative ED estimates for a 5-year-old undergoing various examinations at our institution. An appreciation can be gained of the ascending dose impact from conventional radiography through fluoroscopy, nuclear medicine and CT, with considerable overlap, and converging with diagnostic PET-CT.

A common perception is that CT is the modality of greatest dose concern. Although this is true in terms of population impact from increasing utilization and broadening applications, if we consider the ED of an individual examination, several radioisotope studies (including the now almost retired gallium scan, 20–40 mSv) and higher dose, complex interventional procedures can be of similar or higher dose. Furthermore, as dose-saving technologies advance and we learn to tailor our studies to clinical indication, “the dose of a pediatric CT” becomes a meaningless phrase. An increasing number of specialized CT protocols with ED <0.5 mSv (including cardiac angiography, HRCT, pectus evaluation, 3-D head, and low-dose paranasal sinuses), are an order of magnitude lower in dose than a routine abdomen/pelvis examination. There is a 50-fold dose factor between a 0.2-mSv and a 10-mSv CT examination.

The age and weight range of our patients present particular challenges to pediatric dosimetry. Pediatric EDs are often quoted for a typical 5-year-old patient, yet we might require knowledge of the dose to a 3-kg newborn or a 100-kg teenager, a daunting task. Factors affecting the relationship between age, or weight, and ED are complex and vary according to imaging modality and the technical parameters chosen. The relationship might be proportional, inversely proportional or relatively independent.

If we identify a cohort of similar-age children undergoing the same examination at one institution, even with established and consistently applied protocols, considerable variability in radiation dose is found. Contributing factors include patient weight and height, (influencing exposure factors, magnification mode and collimation in radiography and fluoroscopy, administered radioisotope activity in nuclear medicine, mAs/kVp selection, tube current modulation response and scan length in CT); patient disease factors (influencing fluoroscopy time, magnification mode, and number of exposures/DSA runs in diagnostic and interventional fluoroscopy); and operator factors (influencing fluoroscopy time, collimation, magnification and exposures in fluoroscopy and scan length in CT). Dose variability for patients within an age group is at least $\pm 20\%$, often nearer 50%, and can be significantly higher for procedures where the needs of the examination are determined by the pathology or anatomy encountered. An uncomplicated peripherally inserted central catheter (PICC) placement can be performed with an ED estimate <0.1 mSv, but the most challenging might result in an ED of 1 mSv, 10-fold higher.

Fig. 1 Effective dose estimates for a 5-year-old based on institutional data, Hospital for Sick Children, Toronto. (PICC peripherally inserted central catheter, CVL central venous line, G-tube gastrostomy tube, DMSA dimercaptosuccinic acid, CT Head C– single-phase CT head, CT Head C–/C+ dual-phase CT head, atten. CT attenuation-correction low-dose CT)

Variability in radiation dose among institutions is well documented. Recent publicity has highlighted variability in adult and pediatric CT doses. The phenomenon is not new. Past survey data for plain radiography and fluoroscopy doses have demonstrated significant inter-institutional variability; but the impact on the patient is greater for higher-dose examinations. Variability in mean ED for a similar CT examination is commonly 2- or 3-fold, can exceed a factor of 10, and is a consistent finding in studies from all regions of the world.

Hence, we have moved from a simplistic expectation of “the dose” of a particular pediatric examination to a scenario where dose ranges or ballparks more accurately reflect reality. The intrinsic uncertainties and margins of error inherent in effective dose estimation, combined with intrainstitutional, inter-institutional and age-dependent variability, result in a range of potential dose associated with a particular examination. Within this range lies the dose which may be received by an individual patient.

Calculating such ED ranges or ballparks is challenging. However, the equal or greater challenge is to put the results into meaningful and relevant context for patients’ families and referring physicians. To most people, an mSv value has little meaning. Some manner of risk model must be applied. Comparison can be made to an equivalent number of a low-dose procedure such as a chest radiograph, a time-equivalent period of background radiation, or analogies drawn to risks we take in everyday life, or medical risks including those associated with surgery, anesthetics and adverse drug

reactions. Alternatively, age-related estimates of excess malignancy risk per mSv, essentially based on atomic bomb survivor data and summarized by BEIR VII, can be made. Such risk estimates are themselves subject to considerable uncertainty; the use of broad categories of risk (to an order of magnitude) is appropriate rather than quotes to a single digit. Each approach can help conceptualize potential risk; each has its own merits and limitations, advocates and detractors. The science of risk perception is a complex field.

Ultimately, the issue is of the *balance* of risk and benefit. The particular benefits of an imaging study might enable a specific diagnosis, exclude a potentially serious condition, allow treatment to be started, or direct change in management. Accessibility and wait time, the risk of not having important information, a delay in information or lack of the best information are all part of this balance.

With an appropriate clinical indication, the risk-to-benefit balance will usually be in favor of performing the examination. However, a conscientious assessment is necessary before each imaging study involving ionizing radiation. Together with our medical physics colleagues, we must work toward providing ballpark dose and risk information, which might be used as part of this informed discussion, while acknowledging that it is an imperfect process, with considerable inherent uncertainty and variability. Furthermore, establishing an overview bank of knowledge for ourselves and our referring physicians will help us identify areas of referral concerns, develop clinical management guidelines and target particular examinations for further dose-reduction strategies.