

Size-specific Dose Estimation for CT: How Should It Be Used and What Does It Mean?¹

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Owing to rising concerns about ionizing radiation from medical imaging, the National Council on Radiation Protection and Measurements investigated the growth in the use of imaging procedures that involve ionizing radiation and the collective radiation dose the US population receives (1). In 2006, medical radiation exposure of the US population had increased by approximately 600% compared with that in the early 1980s. Computed tomography (CT) is the greatest contributor to the growth in ionizing radiation exposure from medical imaging, representing 12% of the imaging procedures that use ionizing radiation but contributing 46% of the collective dose to the US population.

The heart of this controversial issue is the difficulty in estimating the health risks of this exposure to radiation and in measuring the dose an individual patient absorbs during a CT scan. As imaging professionals and medical practitioners have become increasingly concerned about these issues, they have searched for a simple way to express the amount of radiation a patient receives while undergoing an imaging examination. Many were quick to adopt the effective dose as a simple expression of patient dose, not realizing that the effective dose is intended to represent the dose to a population of patients. The effective dose is derived from measurements in an idealized phantom that integrates the relative weighting of the radiosensitive organs and does not reflect the morphometrics of an individual patient.

Imaging practitioners who are skilled in radiation dose monitoring and control have a more expansive understanding of the root metrics of effective dose, primarily the dose length product, and secondarily, the volumetric CT dose index ($CTDI_{vol}$). However, they may be surprised to learn that $CTDI_{vol}$ is

a metric of radiation output, not of patient dose. The exposure to radiation is the same whether measured in a block of wood or in a patient's torso. These misinterpretations have caused some confusion among imaging practitioners and have thwarted our collective ability to develop effective strategies for managing individual patient doses at CT.

A breakthrough occurred in May 2011, when the American Association of Physicists in Medicine (AAPM) released report 204, "Size-Specific Dose Estimates in Pediatric and Adult Body CT Examinations" (2). Four teams of investigators used four different techniques to estimate conversion factors to translate $CTDI_{vol}$ measurements to true measurements of dose on the basis of the thickness of the patient's torso. Two of the four teams relied on empirical measurements recorded in anthropomorphic and cylindrical polymethylmethacrylate phantoms, while the other two conducted Monte Carlo simulations of voxelized patient and mathematic cylinder phantoms. The teams combined their results to derive coefficients to convert reported $CTDI_{vol}$ values to patient dose estimates at the center of the scanned volume. In spite of the different techniques, the dose coefficients that the four research groups determined were remarkably consistent, giving credence to this approach for size-specific dose estimation (SSDE). The teams used four different measurements of torso thickness to represent patient size: the anteroposterior dimension (AP), the lateral dimension (LAT), the sum of the dimensions (AP + LAT), and the effective diameter (square root of the product of AP and LAT). They also assessed the potential of using standard size estimates based on patient age, as reported in the International Commission on Radiation Units and Measurements Report 74 (3).

Historically, $CTDI_{vol}$ has been measured by using one of two available

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See also the articles by Brady and Kaufman and Christner et al in this issue.

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polymethylmethacrylate phantoms, one measuring 16 cm and the other measuring 32 cm in diameter. The phantoms were designed primarily for adult imaging, with the 16-cm phantom intended for the adult head and the 32-cm phantom intended for the adult body. One of the compelling challenges in pediatric CT dose estimation is determining which phantom to use for CTDI_{vol} measurements in pediatric body imaging applications. Some manufacturers have used the 16-cm phantom and others have used the 32-cm phantom. Use of the 32-cm phantom has been presumed to underestimate the dose that pediatric patients receive, but specifics regarding the magnitude of this error relative to the age and size of the patient have not been determined.

In this issue of *Radiology*, Brady and Kaufman (4) explore practical issues regarding the use of the AAPM report 204 (2) in clinical practice. They tested the variation among the methods proposed to estimate patient size and dose. The authors concluded that the combination of the AP and LAT dimensions, either the sum or the square root of the product, produced less variability in SSDE than did either measurement used individually. This is supported by the nonlinear relationships between effective diameter and both AP and LAT dimensions, as shown in AAPM Report 204. Here, the nonlinearity associated with the two orthogonal dimensions is complimentary, accounting for the linear relationship between the sum of these two dimensions and the effective diameter.

Perhaps more importantly, Brady and Kaufman have shown that the SSDE provides a better estimate of absorbed dose than does presuming a one-to-one relationship between absorbed dose and CTDI_{vol} measured with the 32-cm polymethylmethacrylate phantom. Moreover, for pediatric patients who weigh less than 36 kg (typically those aged 8 years or younger, as shown in Figure 3), the 16-cm diameter CTDI phantom is a better choice for CTDI_{vol} measurements because SSDE correction is not needed for this demographic. This has important impli-

cations for equipment manufacturers who have relied on 32-cm phantoms for their CTDI_{vol} measurements for pediatric body imaging applications. In addition, the authors have shown that CTDI_{vol} measurements recorded with the 32-cm phantom do not need correction with SSDE in patients who weigh 100–140 kg owing to the close approximation of SSDE from the CTDI_{vol} measurements in patients of this weight range. For patients who weigh 36–100 kg, CTDI_{vol} measurements underestimate patient dose, and for those greater than 140 kg, CTDI_{vol} overestimates patient dose. The equivalency of SSDE and CTDI_{vol} in the 100–140 kg range has fewer practical implications than does the close approximation of patient dose with CTDI_{vol} when measured with the 16-cm phantom in smaller pediatric patients. Manufacturers and practitioners should heed both conclusions, but practitioners will probably benefit by standardizing a workflow that calculates SSDE for all patients to avoid potential errors that may be introduced by applying SSDE selectively.

Just when radiologists started feeling comfortable with these exposure and dose metrics, they were introduced to automatic exposure control (AEC), which created more questions. Would increasing the tube current in heavier patients to maintain uniform image noise have an effect on the dose to the internal organs? Would the dose increase be commensurate with the increased exposure, or would the dose stay the same or even decrease owing to the increased attenuation of the surrounding tissue. Two prior studies (5,6) showed that the increase in dose to internal organs was commensurate with the increased exposure associated with AEC in heavy patients. Israel et al (5) showed that, although the exposure varied by a factor of three between individuals who weighed 60 kg and those who weighed 100 kg, the dose to the liver varied by a factor of two when the tube current was allowed to adjust for a constant noise index. In a prior phantom study, Schindera et al (6) showed a similar relationship between radiation exposure and dose when AEC was used

to maintain constant image noise in phantoms of various sizes.

Christner et al (7) reach a different conclusion. In this issue of *Radiology*, they explore the relationship between AEC and patient dose as estimated with SSDE. Although the exposure was proportional to patient size, SSDE was independent of patient size. Specifically, with AEC, CTDI_{vol} increased from 12 to 26 mGy as the sum of AP and LAT dimensions increased from 42 to 84 cm. However, Christner et al used a different implementation of AEC than that reported previously. Israel et al (5) and Schindera et al (6) used the AEC system implemented by GE Healthcare (Milwaukee, Wis), whereas Christner et al used the AEC system implemented by Siemens Healthcare (Forchheim, Germany). Christner et al explain that the AEC studied in their work requires lower noise values in children and allows higher noise values in obese adults relative to that in adults of standard size. In comparison, the AEC systems used by Israel et al and Schindera et al produced a constant level of image noise regardless of patient size.

SSDE allows estimation of the dose at the center of a certain CT scan range, and it does not take into account variations in dose based on variations in scan length. Moreover, the presumption with SSDE is that patients are centered in the CT gantry so that magnification effects are minimized. Finally, SSDE cannot be used for estimation of organ dose, and thus, it cannot be used to estimate effective dose, which is not intended for individual patient dose estimation.

In spite of these limitations, estimation of patient dose with SSDE from radiation exposure metrics such as CTDI_{vol} is a great step forward in monitoring and controlling the CT imaging radiation dose. The work by Brady and Kaufman (4) helps us to understand which phantom sizes are most appropriate for measuring radiation exposure in children of various sizes and which patient size estimation methods are most appropriate for estimating

patient dose. The work by Christner et al (7) helps us to understand the effect of using AEC to determine radiation exposure and patient dose in patients of different sizes. Authors of both studies present important information for CT equipment manufacturers on phantom sizes appropriate for children and the design specifications for AEC tools. Further work is needed to refine SSDE to provide more precise estimation of patient dose and to extend SSDE to predict organ dose and effective dose. The use of the SSDE will also be important in the use of registries, allowing for more meaningful comparisons of dose indexes.

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