Through the Looking Glass Revisited: The Need for More Meaning and Less Drama in the Reporting of Dose and Dose Reduction in CT[1]

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"When I use a word," Humpty Dumpty said in rather a scornful tone, "it means just what I choose it to mean — neither more nor less."

"The question is," said Alice, "whether you can make words mean so many different things."

"The question is," said Humpty Dumpty, "which is to be master— that's all."

Lewis Carroll, *Through the Looking Glass*

In manuscripts submitted to *Radiology*, the term *low-dose* computed tomography (CT) is often used but rarely well defined. No quantitative definition exists to indicate how low the dose in low-dose CT must be. A given CT examination can, thus, be "low dose" only as compared with an examination with a higher dose, commonly referred to as *standard-dose CT*. Likewise, however, no precise definition of the term *standard dose* exists. Any definition of low dose is, therefore, substantially limited by its relativistic foundation. In addition, the term *low dose* suffers from several other important drawbacks.

In this editorial, we will discuss the drawbacks of the term *low dose* and explain why we believe that this term should no longer be used. Then, we will summarize preferable approaches used to quantify CT-related radiation dose. Finally, we will give recommendations on how CT-related radiation dose should be reported in manuscripts submitted to *Radiology*, with a special emphasis on the importance of size-specific-dose-estimates.

A first drawback of the term *low dose* is that its meaning is subject to considerable variation over time. The sustained efforts of radiologists and physicists to reduce CT radiation dose are not the result of a single, binary, evolutionary paradigm shift in the history of radiology. They rather reflect the ongoing efforts of radiologists, physicists, and manufacturers to reduce the dose administered in diagnostic examinations. These efforts have been promoted by the awareness of the potential health risks caused by radiation, by changing image quality requirements, by a changing spectrum of clinical indications, and by changes in technology. In CT, the ongoing efforts toward technique optimization and dose reduction are not linear and have been accelerated by factors such as the development of new generations of CT scanners; the introduction of automated exposure control, including tube potential optimization; the use of noise-reduction algorithms; new image reconstruction algorithms; and, last but not least, the increasing awareness of the general public, media coverage, and governmental input. Thanks to these efforts, CT examination protocols that were considered low dose a decade ago are now a widely accepted clinical standard. Likewise, we should expect that CT protocols currently considered low dose will become the clinical standard in a very foreseeable future. Therefore, at any given point in time, the term *low dose* is accurate only in the short run. There certainly is a limit to a reduction in dose, determined by the photon requirements to keep an image at an acceptable noise level. Given the acceleration of technical innovation, however, the already fleeting meaning of the term *low dose* is at risk for obsolescence at a steadily increasing rate.

The National Lung Cancer Screening Trial (NLST) provides a recent illustration for this trend (1). The technical

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CT parameters on which the protocols for this trial are based were published in 1999 (2). According to those parameters, the trial was explicitly defined as a low-dose CT screening study. When the trial started in 2002, the examination protocols could still be considered to represent low-dose CT. However, the CT protocols required 120–140 kVp and were performed without automated exposure control, resulting in an estimated effective dose of 1.5 mSv per examination (1). Today, voltage settings of 140 kVp have been widely abandoned (3), the systematic use of automated exposure control is considered the standard of care (4–6), and an estimated effective dose of 1.0 mSv is considered to be a reasonable upper limit for CT examinations aimed at detection and follow-up of lung nodules (7). From this perspective, the use of the term *low dose* for CT protocols of the NLST no longer appears to be justified, a mere year after the study was completed.

A second drawback is that the meaning of low dose is subject to considerable variation geographically. This geographic variation has many facets. It is explained in part by differences in the regional awareness of issues related to CT radiation dose. These differences triggered the publication of regional guidelines for CT dose reduction, which reflect differences in definition of these terms geographically. For example, the European guidelines for maximum organ-specific CT doses are recognized to be more stringent than similar guidelines from non-European countries (8). A more practical aspect of geographical variability is the so-called average patient or standard patient to which many publications about the assessment of CT radiation dose reduction refer. The precise size and weight of this average patient, however, may substantially vary in different regions and is larger in the western hemisphere and smaller in countries of the developing world. According to these changing differences, the World Health Organization (WHO) does not use fixed thresholds but rather ranges of body mass index to define categories such as "normal," "overweight," or "underweight" (9). In addition, WHO constantly adapts these ranges with respect to geographic changes (9). The overall consequence of these geographic considerations is that, for the standard patient at the same point in time, low dose can mean something very different in two distinct countries or continents (10).

A third drawback is that the meaning of *low dose* is subject to considerable variation between and, potentially, within patients. Before the introduction of automated exposure control devices, the calculation of the CT dose applied to a given patient (ie, the radiation output of the scanner, or CT dose index) was relatively straightforward. It was determined by using single tube current settings, typically 120 kV tube potential. This made CT dose index levels relatively easy to calculate and compare among different CT scanner models, protocols, and patients (11). With the introduction of automated exposure control, individual factors such as the body habitus, body circumference, and body position in the CT gantry with respect to the center of rotation started to substantially affect the CT dose index values used in clinical scanning (4–6).

A fourth drawback is that the use of the term *low dose* is at risk for considerable conceptual imprecision. In 1999, scientific articles listed in PubMed and containing the words "low dose" and "CT" in either their title or abstract accounted for 0.85% (61 of 7159) of all articles with "CT" or "computed tomography" in the title or abstract. In 2010, the same proportion was 2.29% (394 of 17239), which, thus, is almost a factor of three higher. This increase likely reflects the increased interest in CT radiation dose over the past decade. Now that previous low-dose CT has effectively become standard-dose CT at many institutions, a tendency appears to connote further efforts toward dose reduction with additional adjectives to connote increasingly diminutive low dose. First reports about "extremely low dose" and "ultralow dose" CT have, indeed, already appeared in the literature (12–14). As ongoing efforts to reduce CT radiation dose continue, concerns about overstretching the lower end of the terminology scale will no doubt be raised. What will follow ultralow dose CT? When will "super-extra-nano-low–dose" CT emerge? The frightening perspective is a tower-of-Babel–like scenario, with an increasing number of low-dose–like terms without definition, which will be a source of confusion among both patients and radiologists. From an editorial perspective, this tendency clearly is neither desirable nor sustainable. Finally, similar to the sometimes deceptive qualitative label "light" on various consumer goods, "low dose" might falsely assuage potentially justified concerns of patients and physicians, rather than provide them with meaningful quantitative information required for informed decision making based on a responsible comparison of realistic risks and benefits.

We believe that the only remedy to these concerns is the general avoidance of the term *low dose* and its replacement by terminology that will allow precise and reproducible comparisons of dose between and within studies. One possible approach to this issue would be to report the effective dose. In fact, a number of authors have unfortunately used this metric to report patient dose and the magnitude of dose reduction in manuscripts submitted to *Radiology*. Effective dose is expressed in millisieverts and represents a calculated parameter that cannot be directly measured. The calculations are based on the number and a hypothetical relative radiosensitivity of the organs exposed during a given CT examination protocol. The organs are then assigned a weighting factor, as defined by the International Commission on Radiological Protection (ICRP) (15). However, these weighting factors are periodically reassessed and have already been changed three times since the concept was introduced in 1977 (16–21).

In its most recent report (21), the ICRP emphasized that effective dose is defined only for the ICRP reference human. This reference human has organ doses that are the average value of the ICRP reference adult male and adult female. Thus, effective dose cannot be used to describe dose to any individual, notably because it avoids consideration

of the effect of patient size on dose and because organ risk coefficients are averaged over both sexes and all ages. For individual risk assessment, specific organ doses to each individual in the cohort must be considered.

The applicability of effective dose in medicine is limited to comparing the effective dose value, for example, from a coronary CT to a catheter-based coronary angiogram or a nuclear medicine myocardial perfusion scan. The effective dose of a given examination can also be compared with background radiation levels. However, effective dose cannot help to define *low dose* more precisely (16). There is increasing awareness of the severe limitations of effective dose when specifically used for dose-associated risk assessment (16). Therefore, the authors of recent publications recommend that, given the inherent uncertainties and oversimplifications involved with the use of effective dose, this parameter should not be used for dose-related population risks (17). We emphasize this recent recommendation by discouraging the use of effective dose in this context.

Instead, studies in which CT dose levels are evaluated and compared should consistently report the following four parameters: *(a)* volume CT dose index ($CTDI_{vol}$), *(b)* dose length product (DLP), *(c)* a measure of patient dimensions, for example the effective diameter (8,22–27), and *(d)* the size-specific dose estimate (SSDE).

$CTDI_{vol}$ specifies the amount of radiation delivered by the scanner for a specific CT examination. It is sometimes referred to as the scanner radiation output, and its unit of measure is the milligray. Being a scanner-dependent parameter, $CTDI_{vol}$ is displayed in the dose protocol of virtually every current CT scanner. $CTDI_{vol}$ is precisely defined by international standards organizations and by regulatory agencies (27). Moreover, $CTDI_{vol}$ is the metric used by the American College of Radiology for CT practice accreditation (28). Finally, the equipment required to measure $CTDI_{vol}$ is available worldwide. These attributes have all contributed to the current universal acceptance of $CTDI_{vol}$ as preferred scanner-specific parameter to describe CT dose (29). An important requirement for the accurate interpretation of $CTDI_{vol}$, however, is information about the phantom size that was used to estimate this parameter. Both 16- and 32-cm phantoms are currently used by various manufacturers for calculating their CT dose index reference, which can lead to ambiguity if the phantom size is not specifically stated.

The limitations of CT dose index in general and of $CTDI_{vol}$ in particular have been extensively discussed in the literature (30,31). First, CT dose index is measured by using a standardized, cylindric, homogeneous phantom. This phantom cannot reflect the wide variety in sizes, shapes, and attenuation characteristics of the human body. Second, CT dose index reflects dose to air and not dose to tissue. CT dose index is, thus, quite remote from actual tissue dosimetry. Third, the 14-cm length of the body CT dose index phantom does not provide a sufficiently long scatter path relative to the typical length of a human torso. Therefore, CT dose index may underestimate the true dose delivered to the patient. Fourth, the current 100-mm integration length is sufficient for measurements of dose details for a beam width of several centimeters, but it is insufficient for beam widths greater than 10 cm. Fifth, CT dose index does not indicate the dose to a specific anatomic location if the patient is stationary during multiple scans, such as in perfusion CT and during interventional procedures (30,31). Despite these limitations, however, $CTDI_{vol}$ currently remains the cornerstone parameter in the assessment of CT dose.

$CTDI_{vol}$ is independent of scan length and patient size. Therefore, $CTDI_{vol}$ alone does not quantify how much radiation a specific patient receives but simply indicates how much radiation is directed toward the patient. To translate the reported $CTDI_{vol}$ for an individual or a patient cohort into a more meaningful measure of dose, additional information about scan length and body dimensions must be provided. Although scan length can be given in centimeters, it is more elegantly represented by DLP. DLP is the product of $CTDI_{vol}$ and the scan length in centimeters, and its unit is milligray-centimeters. $CTDI_{vol}$ and DLP are considered by some as the only two dose parameters that can be universally interpreted (29). In addition, DLP and $CTDI_{vol}$, have the advantage that they can be read from the dose protocol directly on the scanner console at the time of the CT examination.

Despite their practical advantages, however, both $CTDI_{vol}$ and DLP measure scanner output only, and because they do not include information about patient dimensions and the region of the body examined, they cannot reflect individual patient dose. Therefore, a third parameter that reflects patient dimensions is needed. Measurement of the largest anteroposterior and transverse diameters of the scanned body region is probably the most practical means to accomplish this task. In fact, measurements of these diameters can be performed both on the topogram (ie, the CT projection radiograph used to determine the anatomic scan range) before a particular scan is initiated and on the reconstructed transverse images after completion of the scan. Alternative measures, such as calculating the body mass index (32), require gathering potentially remote information from the clinical charts that might not be readily available. In addition, global body size indicators such as weight or body mass index do not necessarily represent the attenuation in specific body regions, because patient weight can be distributed very differently among individuals. In contrast, patient diameters can be measured in the scanned region at every single CT examination by using the digital calipers on the CT console.

The American Association of Physicists in Medicine Task Group 204 report (33) defines the effective diameter as the square root of the anteroposterior diameter times the transverse diameter. The report also provides tables based on the effective diameter aimed to find the conversion factor f_{size} that, when multiplied by $CTDI_{vol}$, will yield an SSDE for a given patient and CT examination: $SSDE = f_{size} \times CTDI_{vol}$. Thus, other than just quantifying the dose output values for a given CT examination by using $CTDI_{vol}$

and DLP, SSDE can approximate the dose that the individual patient absorbs from the CT examination and could, thereby, pave the way to a more individual approach for estimates of radiation risk from CT examinations (33). If authors can calculate SSDE directly, as described above, this single value will be an alternative single metric that would convey dose in a reasonably accurate manner. Therefore, whenever an author reports average doses among a cohort, he or she should also provide averages in terms of SSDE. Reporting only average $CTDI_{vol}$, average DLP, and average effective diameter will not result in the calculation of a correct average SSDE, however, due to the nonlinear relationship between $CTDI_{vol}$ and SSDE; SSDE must be calculated for each patient individually before a cohort average can be calculated.

To warrant a comprehensive description of their results, authors should thus report the following four parameters: $CTDI_{vol}$, DLP, effective diameter, and SSDE. $CTDI_{vol}$ and DLP will provide information about scanner radiation output. The effective diameter will provide information about the dimensional characteristics of the study population. SSDE will provide an approximation of the dose absorbed by the individual patient.

In summary, we are beginning to require authors to provide $CTDI_{vol}$, and DLP as the primary dose-related parameters for all studies involving CT, notably those in which CT dose levels and CT protocols are compared. Whenever possible, a measure of effective diameter should be included, and SSDE should be calculated on a per-patient basis. Together, these parameters will provide precise quantification of both scanner output and patient dose. On the other hand, we will be increasingly critical of the use of the term "low dose" in manuscripts submitted to *Radiology* and will discourage authors from using this term. Instead, authors should characterize their CT examination protocols with the four precisely defined parameters described above, with an emphasis on the importance of SSDE. Rather than vague qualifiers, these parameters will warrant the clinical applicability and reproducibility of the studies published in *Radiology*. The vast majority of articles in our journal are aimed ultimately at improving patient care. One way to help achieve this goal is to provide our readers with articles that use meaningful and universally understood terminology. Unfortunately, the term *low dose CT* does not satisfy this standard and, as a consequence, should no longer be used.

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