National Conference on Dose Reduction in CT, with an Emphasis on Pediatric Patients

Otha W. Linton[1] and Fred A. Mettler, Jr.[2]

The clinical value of CT is unquestioned, and the uses of newer helical and multidetector units are growing. The dose received by some patients, particularly children, is higher than desired and must and can be reduced without any significant loss of diagnostic information. These were the conclusions of a 2-day symposium on the subject of CT dose conducted November 6–7, 2002, by the National Council on Radiation Protection and Measurements.

CT dose reduction will require a combination of approaches, a series of speakers agreed. These include user education for physicians and radiologic technologists, development of technique charts by medical physicists, development of automatic exposure control devices by manufacturers, and possible retrofits of these devices for older machines. It also will require creation of a climate of opinion in which radiologists will demand attention to dose reduction in their purchase of new CT scanners, one industry participant commented.

The National Council on Radiation Protection and Measurements conference was more a work in progress than a starting call to action, said the conference chairman, Fred A. Mettler, Jr., of the University of New Mexico at Albuquerque. He observed that articles about excessive CT dose have multiplied in the radiologic literature and presentations on the subject have appeared on national society programs during the past year. The American College of Radiology (ACR) has announced a new CT facility accreditation program. "Our task is to define where we are on CT dose and to make recommendations on where we go from here."

Recommendations derived by working groups and approved by a consensus of conference registrants accompany this article as Appendix 1.

"CT now represents the largest single source of medical exposure and its use is increasing rapidly. In some university departments, CT scanning has grown to be about 15% of the total number of examinations but now accounts for about 70% of the dose delivered," Mettler said. "CT procedures could account for as much as 60% of manmade radiation exposures to Americans."

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Is the dose from helical and multidetector CT scanning procedures too high? "Available data for solid tumors from the atomic bomb survivors are consistent with linearity down to a dose of 0.2 Gy and perhaps to 0.05 Gy," explained Eric Hall, a professor of radiobiology at Columbia University in New York City.

> A threshold in the milligray region cannot be ruled out, but there is no sign of a threshold at doses of the order of a few tens of milligray. Individuals exposed 50 years ago to doses comparable to those associated with helical computed tomography today show a small but statistically significant excess incidence of cancer.… It is clear that young children are more sensitive to the radiation-induced malignancies than mature adults. This raises special concern about the use of CT in pediatric patients.

The emphasis on children reflected an estimate made by Brenner et al. in the *AJR* [1] that 600,000 abdominal and head CT examinations annually on children under the age of 15 years could result in 500 deaths from cancer attributable to CT radiation. That article drew considerable public attention. In the same issue of *AJR*, two other articles on CT imaging of children commented that few CT facilities made any adjustment in technical

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factors to reflect the age or size of the patient undergoing CT [2, 3].

"The truth is that we were asleep at the switch on the issue of CT dose," said *AJR* editor in chief Lee F. Rogers in a keynote address to the symposium.

> CT scanning has had such incredible value in diagnosis that it has changed radiology and several other specialties. We do less angiography. We do no pneumoencephalography, little myelography and our surgical colleagues have almost given up exploratory surgery and open biopsies. We in radiology were more interested in better images and new applications. The computer adjusted to compensate for overexposures and we failed to appreciate the extent of dose without a blackened X-ray film to remind us.

In 2000, Americans received 57 million CT examinations from 7645 CT facilities, according to Stanley H. Stern of the United States Food and Drug Administration's Center for Devices and Radiological Health. He described preliminary findings from that year's Nationwide Evaluation of X-ray Trends study, which surveyed CT techniques and doses in 263 facilities in 39 states. The average facility surveyed performed 144 CT studies a week. Body examinations held a 3:2 relationship to head and spine studies, with a very few interventional procedures and a few studies for radiotherapy planning. In the survey sample, 81% of the scanners had helical scanning capability. Only 5% were capable of performing CT fluoroscopy. Only 43% of the facilities indicated that they made any adjustment in technique for pediatric patients. About three fourths of the scanners were located in hospitals.

Pediatric CT Concerns

Concerns about CT doses to pediatric patients prompted earlier activities by the Society of Pediatric Radiology involving Thomas Slovis of Wayne State University in Detroit and Donald P. Frush of Duke University in Durham, NC. "We have seen a 200% increase in pediatric CT examinations in the past few years," Frush told the conference.

> Our studies reflected a lack of attention to the potential hazards for children or to the need for reducing dose according to the body size of a small patient. Four fifths of CT studies of children are not managed by pediatric radiologists. However, in recent months following attention to the problem, we have seen indications that some centers have gotten the message. It is my impression that people are more sensitive to indications for CT studies and to the implications of repeated examinations.

Slovis stressed the concern about repeated CT examinations of children. He urged adjustment of technique for different body parts, as well as beam limitation to the area of interest. "We have all emphasized image quality even when it involved more dose; now we need to focus on the image quality needed to make a diagnosis with reduced dose, rather than the best possible image."

It is important to be able to determine the effective dose for a CT scan, particularly for children, said Robert L. Brent, a pediatrician from the DuPont Hospital for Children in Wilmington, DE. He said:

> Not only are children more sensitive to radiation than adults, but they will have more years in which cancerous changes might occur. Recording doses or being able to reproduce them accurately can be important whenever a question arises about effects of radiation exposures. Because of our continuing uncertainty about added radiation risks in children, we need both prospective and retrospective studies to give us the needed information.

Adult CT Concerns

Joseph T. Ferrucci of the Boston University Medical Center said:

> CT scanning is incredibly effective and has become standard radiology because it lets us see much more than we could with conventional X rays. It also increases the confidence of our referring physicians in our contributions in almost every clinical area.

Ferrucci explained:

> With the advent of virtual colonoscopy based upon CT techniques, we have a real breakthrough in bowel screening and cancer detection. But, to a growing list of CT-dependent diagnoses, we should add a list of other conditions for which ultrasound, MR imaging, or even conventional radiography may be the appropriate modality.
>
> For undefined problems of the biliary duct, the gynecological system, the thyroid, the scrotum, carotid vessels and fistulae, sonography is preferred. For headaches, seizures, dementia, gait disorders, low back pain, and sports injuries, MR imaging should be first.
>
> CT-dependent diagnoses include: head injury, seizure, stroke, mental status change; tumors and sarcomas of lung, pancreas, and kidney; management of lymphomas, colon cancer; liver disease, including cirrhosis and jaundice; trauma, especially of the head, abdomen, and chest; acute abdominal pain, namely, appendicitis or kidney stone; complex fractures, especially of neck or pelvis.

"Today, the most controversial use of CT is for screening procedures on nonsymptomatic persons without physician referrals," said Bruce J. Hillman of the University of Virginia at Charlottesville. He explained:

> If walk-in CT screening centers continue to grow, the cost impact on the health care system could be tremendous, without any evidence as to the cost-effectiveness of such screening. Even if third parties refuse to cover such screening, the charges paid by patients will add millions of dollars to national health expenditures.

He added that it would be difficult and expensive to design a study that could measure the value, if any, of such screening programs. "There are plenty of anecdotes, but that is not valid proof."

Howard Forman of Yale University in New Haven, CT, agreed with Hillman. He added:

> Every new development in CT scanning creates greater demand for examinations on more body systems and problems. CT scanning demand does not fit standard economic patterns about supply, demand, and price.

To some extent, this is because CT is part of medicine, which does not fit those patterns. The acceptance of CT by patients and referring physicians is not inhibited by elements of cost or potential danger, he explained:

> Hospitals need the volume to pay for the service. Third parties get no independent information and generally accept the bills. The pressure is for the radiologist to provide the CT examination, not to suggest alternatives or no examination at all.

CT procedures are the only area in diagnostic radiology in which doses have gone up instead of down in the past few decades, said Peter Dawson of the University College in London, England.

> Multidetector units tend to contribute greater dose than single slice units because of a combination of geometric factors and the need for "top and tail" slices for reconstruction. These effects become less important as the number of multidetectors increases (four to eight to 16) but the way the machines are used is a huge factor: more scans, more phases, and bigger volumes all mean higher doses. British studies have reflected a variation of 40 times the dose in using different techniques. That needs fixing.

CT Physics

One problem in addressing CT dose is getting everyone to use the same language, asserted Cynthia H. McCollough of the Mayo Clinic in Rochester, MN. She said:

> We have too many concepts, terms and trade names, and not too few. In particular, we need to agree on how to define or describe CT dose and agree on the terms used for such units. Should we call it CT dose index (CTDI) and, if so, which of its several variants ($CTDI_{FDA}$, $CTDI_{100}$, $CTDI_w$, $CTDI_{vol}$). What role should multiple scan average dose, dose length product, organ dose and effective dose play? We need to agree on when and how to use each one. Perhaps we should declare a moratorium on any new dose concepts and terms until we can sort out what we have now. This is a challenge for physicists and manufacturers.

Michael McNitt-Gray, a physicist from the University of California at Los Angeles, pointed out that technical ways to reduce dose involve defining needed image quality and possibly accepting some trade-offs between dose and image characteristics, which will be task-dependent. When dealing with helical CT scanners, one important factor determining dose is the pitch or advancement of the scanning plane through a patient's body. The radiation dose is inversely proportional to the pitch selected; scans with a pitch of 2 give 50% of the radiation dose of scans with a pitch of 1. However, in some scanners, this results in an increase in effective slice thickness, producing more volume averaging of objects that may be clinically unacceptable. McNitt-Gray also pointed out that the narrower the collimation, the more the penumbral effect and thus the higher the dose. He added,

> One can reduce the photon energy level in kVp for a savings, but if the tube-current exposure time (in mAs) is allowed to increase—to compensate for an increase in noise—then those dose savings will be reduced or even completely offset. Factors of filtration, beam hardening, and noise levels also must be understood and controlled with regard to both radiation dose and the image quality requirements of the imaging task.

The issue of image quality pervaded several presentations and comments from attendees. One commenter reminded the audience that dose reduction that sacrifices diagnostic quality is an unacceptable bargain. A single measure of image quality is difficult to agree on because image quality comprises several interrelated variables—spatial, contrast, and temporal resolution; image noise; and artifact level.

Manufacturers

Many of the technical adjustments needed to reduce CT dose are within the current capability of CT manufacturers, challenged McCollough. She opened a panel discussion by manufacturers' spokesmen by pressing for the provision of automatic exposure controls that would relieve CT users of the need to make manual adjustments for each patient. "We have already seen that busy technologists do not take the time for fine-tuning with each patient. Why not let the machine do it?"

Several speakers, including manufacturers' representatives, emphasized that improved technique charts could provide guidance to CT technologists in setting their scanners for acceptable noise-to-dose ratios. "This is important in the short run because we cannot change all of the machines instantly," McCollough acknowledged. "I believe customers are ready to buy safety features. It's up to the manufacturers to provide and sell them."

Stanley Fox, representing General Electric Medical Systems, said that his company is already working on technical changes to reduce dose from existing CT equipment. He said:

> We have better algorithms, protocols for children, new protocols for cardiac gating studies. We're changing our design to use more of the collimated beam and improving multi-slice matrices. In 2003, we will have a protocol in which patient thickness will control dose modulation. Dose can be cut in half with present equipment while maintaining an acceptable noise factor.

Siemens Medical Solutions already is adding dose reduction features to its CT units, according to Bernhardt Schmidt, representing the company. These include filtration of soft-beam X ray, focal spot tracking, and improved detector efficiency. Siemens is already providing technique charts adjusted for children and neonates. They provide $CTDI_w$ values on a technique scan card so that users can modify their settings by patient size. "Siemens urges its customers to tell their patients about exposure levels and efforts to control dose," Schmidt said.

Philips Medical Systems also has begun a user education program for CT dose control, said Hugh T. Morgan, its representative. Philips and competitive CT units now are required to display dose on scanner control panels, he explained. The CT dose index volume ($CTDI_{vol}$) will be used by each manufacturer, allowing scanner-to-scanner comparisons. However, he noted the actual dose to a specific patient may vary from the displayed dose index, and perhaps a better measure of actual dose is needed. Philips is working with asymmetric detector arrays, optimized beam shaping, and dynamic collimation. Operator manuals are being revised and improved.

Toshiba American Medical Sytems likewise is working on equipment improvements and better technique manuals, said its spokesman, Bryan R. Westerman. The company in 1998 introduced ceramic detectors to improve image quality with less radiation, he explained. Toshiba provides many options for fine-tuning CT technique, more than 360 in all and 144 for children. He agreed that the next step would be to make dose choices more automatic.

A suggestion from the audience that both CT users and patients be given dose information for each examination brought a mixed response. User knowledge was favored, but giving such information to patients without a specific purpose was not. The National Council on Radiation Protection and Measurements, ACR, and other spokesmen for radiation protection and users have expressed reservations about recording and preserving dose readings or estimates for every radiologic procedure.

Users and Regulators

"The relatively new ACR CT facilities accreditation program is processing more than

100 applications for approval and has granted its first seven certificates," said James A. Brink of Yale University, a member of the ACR committee. The CT accreditation program is comparable to other ACR accreditation efforts, he said. It is voluntary. Radiology facilities can apply to ACR and be asked to complete a series of protocols. Phantom and patient images and other data must be submitted. The clinical images must include three studies: a routine head, body, and specialty or pediatric examination plus calculations of $CTDI_w$ data. The ACR used European data to establish its reference doses, Brink said.

"Most radiologic technologists learn CT techniques informally on the job, rather than as part of their basic educational experience," said Anne Edwards of North Liberty, IA, representing the American Society of Radiologic Technologists. "Whatever their good intentions, manufacturers after installing a new CT unit often fail to provide effective instructions to the technologists who will be using it," she complained. "More useful direct explanations and better user manuals would help, as would frequent refresher courses."

The American Registry of Radiologic Technologists offers certification in CT use without any specific requirement for training or experience and is developing a CT training module. "If operators are required to add dose reduction factors to other machine settings, more instruction will be needed," she asserted.

Also, on user education, Rogers contended that radiologists need a commitment to reducing CT doses, rather than a detailed knowledge of technical factors that control CT operation. "The technical factors are the job of the physicist and the manufacturer," he said.

> We need a team approach and behavior modification. That's our job. One alternative would be to regulate our behavior. We should be able to make things better without being told that we have to do it. It's difficult, but we need to look at the problem of overreferrals from some of our colleagues. CT is wonderful, but not every time for every patient.

Jill Lipoti, associate director of the New Jersey Department of Environmental Protection, and thus a regulator, said that regulations should be devised to encourage dose reduction without impeding innovation. "The federal government regulates new equipment and the states monitor old equipment already. We could not be successful as regulators without the cooperation of professional societies and manufacturers."

Thomas B. Shope of the Food and Drug Administration, which regulates all medical equipment, concurred with the need for cooperation. He explained:

> The Food and Drug Administration has had difficulty shaping regulations specifically for CT equipment. This is in part because CT equipment has matured and changed so rapidly and in part because the agency has had limited resources and more pressing problems.

The Food and Drug Administration has tried to coordinate its regulatory standard setting with international guidelines so that manufacturers can design to a single standard.

Otha Linton, representing the International Society of Radiology, addressed the issue of population risk:

> The general public has been told that CT scanning is wonderful and that no one need be afraid of it. Now they are hearing that there may be a problem. We have to be careful about how we express that problem to avoid a rejection phenomenon.

He emphasized:

> It's not the technical details, it is a matter of perception. Radiology has had many crises when people believed that medical radiation could harm them. This was the case when charges were made that screening mammography was dangerous in the 1970s. Our answer was to make it better and safer. But it took a decade to win back public confidence. Dose problems with CT are real but solvable. Our message needs to be that we are solving them.

Four working groups prepared a series of recommendations for action to improve CT use and limit radiation exposure. Their recommendations included programs for user education, equipment modification, clinical applications, and possible regulatory programs.

"The next steps are for a lot of people to look at our recommendations and decide to do something about CT dose on their own," said Edward Staab, National Cancer Institute project officer on the symposium.

> One good result from our sessions is a clear idea that some caring people already are working on dose reduction. In our recommendations, we are asking that several societies and manufacturers commit to greater efforts. In the end, we have to ask that every CT facility take its own action.

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APPENDIX 1. Recommendations

Part of the challenge to participants in the CT dose conference was the development of recommendations for action to reduce patient dose while preserving the unquestioned value of CT examinations. The recommendations that follow are the product of that effort. Four working groups prepared suggestions on user education, equipment modification, clinical applications, and public policy. These were presented to the entire group for review and concurrence.

The four reports overlapped somewhat and have been consolidated into one set of recommendations. In addition to specific action items, the registrants also made suggestions as to which organizations might be willing and able to carry out specific items. Some suggestions represent activities already underway; in the opinion of the group, these activities should be continued or enhanced. The mention of an organization does not connote any commitment from the organization.

The recommendations are:

I. Recognize a CT dose problem that needs correcting and is correctable
- A. CT dose to children is significant; special attention is needed
- B. CT patient surveillance effort needed to determine actual doses received and needed
- C. Accept the “as low as reasonably achievable” (ALARA) principle in seeking solutions

II. Commit to an effective, ongoing dose reduction effort to involve
- A. User education
- B. Equipment modification
- C. Protocol and terminology standardization
- D. Basic research on ways to lower dose substantially

III. Involve major groups in radiology and relating to radiology
- A. Radiology societies: American College of Radiology, American Society of Radiologic Technologists, American Association of Physicists in Medicine, Society of Pediatric Radiology
- B. Manufacturers and standards organizations: National Electrical Manufacturers Association, International Electrotechnical Commission, General Electric, Philips, Siemens, Toshiba
- C. Regulators, public agencies: National Cancer Institute, Food and Drug Administration Center’s for Devices and Radiological Health, Conference of Radiation Control Program Directors

IV. Seek Changes
- A. Standard dose terms: American Association of Physicists in Medicine, International Electrotechnical Commission, National Electrical Manufacturers Association, National Council on Radiation Protection and Measurements, International Commission on Radiation Units and Measures, International Commission on Radiological Protection
  1. Draft a position paper
  2. Conference on terminology

- B. Procedures, protocols
  1. Equipment technique charts, specific to each scanner model, by patient size
  2. Individual patient dose display and recording
  3. CT quality assurance program development

- C. Specific radiographer training for CT operations

- D. Review CT usage patterns
  1. Screening is not recommended at this time
  2. Alternative examinations, appropriateness
  3. Attention to beam area limitation
  4. “Idealized” dose by patient size
     - a. Adequate image quality
     - b. Scanner independent noise index
     - c. Reproducibility
  5. Special attention to pediatric patients

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E. Dose determination studies: Food and Drug Administration's Center for Devices and Radiological Health, American Association of Physicists in Medicine, American College of Radiology

F. CT facility accreditation: American College of Radiology

G. CT facility designation of a medical director responsible for
1. Image quality
2. Dose
3. Appropriateness

H. Periodic appropriateness guidelines review

I. CT facility inspection and studies: Food and Drug Administration's Center for Devices and Radiological Health, Conference of Radiation Control Program Directors

J. Educational efforts
1. Presentations to meetings
2. Development of teaching materials: Food and Drug Administration, American College of Radiology, American Society of Radiologic Technologists, American Association of Physicists in Medicine
   a. Technique manuals, videos, CD-ROMs
   b. Dose reduction protocols and database
   c. Basic CT physics
   d. Quality assurance manuals
3. Consumer education, description of risk
   a. Referring physicians
   b. Regulators
   c. Public health officials
   d. Patients

APPENDIX 2. Reading List

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APPENDIX 3. CT Physics Discussion and Glossary of Terms Used to Describe Radiation Dose by Thomas B. Shope

Discussion

X-ray exposure conditions during CT are unique when compared to conventional projection radiography exposures. These unique conditions include a narrow, fan-shaped X-ray beam that rotates around the patient (Fig. 1). A complete rotation or scan provides sufficient data to reconstruct an image or tomographic section of the irradiated volume. On single-slice scanners the volume imaged in a single rotation corresponds to one slice; on multidetector scanners the volume imaged in a single rotation can correspond to multiple slices.

A three-dimensional coordinate system is necessary for this discussion. The *x*- and *y*-axes are defined by the plane of rotation of the X-ray source, and the *z*-axis is perpendicular to that plane and parallel to the axis of rotation.

During a CT procedure, the patient moves incrementally (axial scanning) or continuously (helical scanning) in a direction perpendicular to the fan beam and the (*x, y*) plane as additional images are produced. Special concepts and terminology have been developed to describe the radiation dose from CT to account for this irradiation pattern as opposed to the irradiation pattern during projection radiography. During a series of CT scans, because of scattered X rays and possible primary beam overlap, the absorbed dose at a point in one slice or section is the result of imaging that section and many of the adjacent sections. CT procedures generally consist of a series of scans or slices, so the dose descriptor initially adopted for CT was one that was intended to be clinically relevant and to approximate the dose from a procedure involving a series of adjacent scans, not a single scan.

In the following discussion, consider the case of a series of *N* single-slice scans with slice width (nominal slice thickness) *T* and increment *I* between scans equal to the slice width ($T = I$). Consider the dose, at a particular point (*x, y*) in a phantom or a patient, measured along a line parallel to the direction of patient movement (*z*-axis). The dose as a function of position along the *z* direction is a dose profile, $D(z)$. (See inset in Fig. 1.) The dose over the width of the center slice of a series of *N* adjacent slices has contributions from adjacent slices but reaches a stable value when the first and last slices of the series contribute no dose to the volume of the central slice (Fig. 2). This limiting value has been described as the MSAD (multiple scan [or multiple slice] average dose, i.e., the $MSAD_{N,I}$). It therefore approximates the dose at this (*x, y*) location over most of the length of the scanned or imaged region.

This limiting value, the dose profile from a series of scans averaged over the slice width at the location of the central slice, can be obtained easily from the dose profile for a single scan measured at the same (*x, y*) location. When obtained from the dose profile from a single scan, this quantity is called the CTDI, or CT dose index. Thus, the CTDI measured from a single scan describes the average dose, the MSAD, at a specific (*x, y*) location along the *z* direction over the central portion of the volume imaged by a series of scans. The CTDI can be considered an index indicating the approximate dose that occurs at a specific (*x, y*) location over most of the length of the scanned volume of the phantom or patient from the series of scans.

Actual measurements of the CTDI, which give the corresponding $MSAD_{N,I}$, are usually performed in a CT dosimetry phantom (i.e., a right circular cylinder of plastic). So, although measurements are correlated to patient dose, the dose measurements do not describe the radiation dose to a specific patient or to a specific organ in a patient. However, they are useful for comparing relative system performance in terms of the magnitude of the radiation dose as a function of system operating techniques and scanning protocol.

The MSAD provides an indication of the absorbed dose at a specific (*x, y*) location in the phantom from a series of scans. Additional calculations, beyond the scope of this brief review, are required to estimate patient organ doses, total energy absorbed, or effective dose from a CT procedure. These are typically estimated using measurements of CTDI, either in a phantom or in air on the axis of rotation, along with computer simulations modeling the human body and the X-ray scattering process. (See the glossary and glossary bibliography for additional information and further references.)

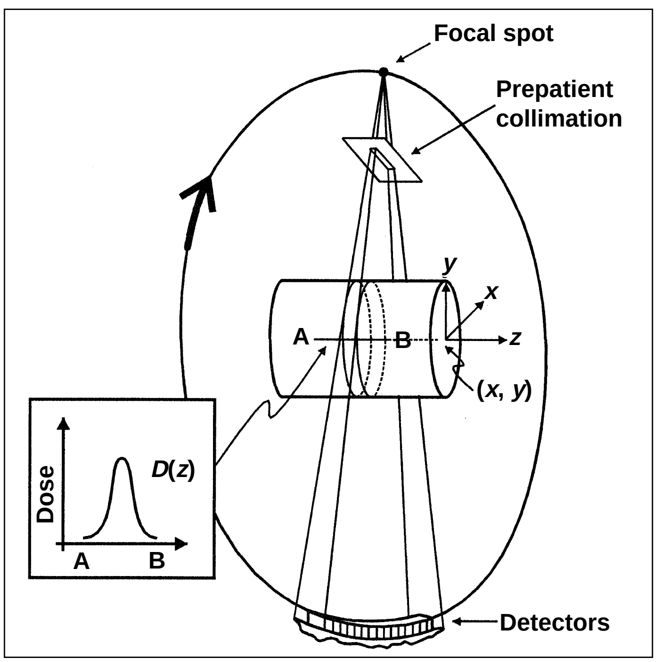

Fig. 1.—Illustration of CT system geometry shows intersection of X-ray beam with dosimetry phantom. Insert indicates idealized dose profile measured along line AB. (Courtesy of Shope TB, Food and Drug Administration's Center for Devices and Radiological Health, Gaithersburg, MD)

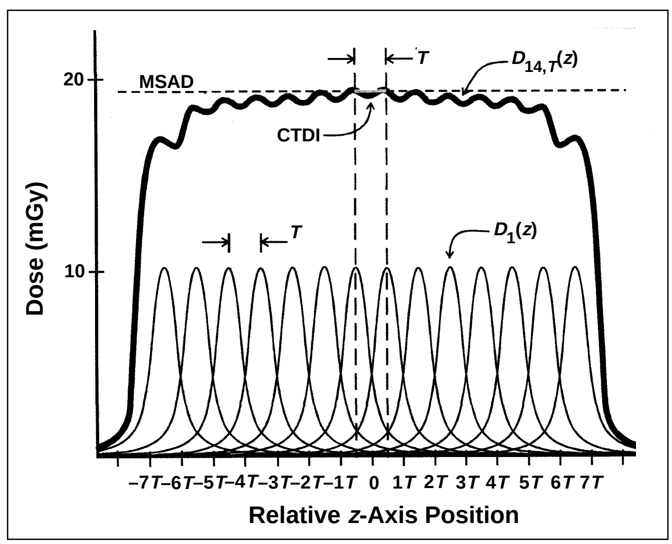

Fig. 2.—Illustration of multiple scan dose profile shows results from series of 14 scans with increment equal to slice thickness (*T*). Multiple scan average dose (MSAD) is given by CT dose index (CTDI) indicated at central portion of multiple scan dose profile. (Courtesy of Shope TB, Food and Drug Administration's Center for Devices and Radiological Health, Gaithersburg, MD)

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Glossary

Dose: Dose, D, means the absorbed dose, which is the mean energy imparted per unit mass. It is measured in joules per kilogram (J/kg). The special name for the unit of absorbed dose is the gray (Gy), where 1 Gy is equal to 1 J/kg.

Multiple scan average dose (MSAD): For a dose profile, $D_{N,I}(z)$, resulting from a series of N adjacent scans in which the first and last scans contribute negligible amounts of scattered radiation to the volume imaged by the central scan of the series, the MSAD is the average value of the dose profile at location (x, y) in the center of the series of scans where the average is over a distance equal to the increment between scans, I:

$$MSAD_{N,I} = \frac{1}{I}\int_{-I/2}^{I/2} D_{N,I}(z)dz$$

where $MSAD_{N,I}$ designates the MSAD for a series of N scans with an increment of I between scans; $D_{N,I}(z)$ is the total dose profile resulting from the doses from all N scans; and the origin of the z-axis is assumed to coincide with the center of the central scan contributing to the dose profile.

CT dose index (CTDI): The integral along a line parallel to the axis of rotation (z-axis) of the dose profile, $D(z)$, divided by nT:

$$CTDI = \frac{1}{nT}\int_{-\infty}^{+\infty} D(z)dz$$

where T is the nominal slice thickness and n is the number of slices (tomograms) imaged simultaneously in a single scan (X-ray tube rotation).

It can be shown for sufficiently large N that

$$MSAD_{N,I} = \left(\frac{nT}{I}\right) CTDI$$

where N is the number of scans in a series of adjacent scans with the same technique factors, I the increment between slices, n is the number of slices obtained in a single axial scan, and T is the nominal slice thickness.

This relationship between MSAD and CTDI permits the average dose at a location (x, y) in the central slice of a series of scans, the MSAD, to be determined from measurement of the CTDI at the same (x, y) location for a single scan.

Modifications and Adaptations of CTDI

The CTDI defined with an infinite integration length is not easily measured. A number of variations have been introduced that ignore the relatively small contributions of the dose profile at distances (values of z) far from the center of the slice imaged or scanned. CTDI may then be approximated by integration over a limited range of the z coordinate.

$CTDI_{FDA}$: The CTDI with integration over a distance equal to 14 slice thicknesses—that is, from $-7T$ to $+7T$. (Integration over a length equal to 14 slices was originally chosen to represent a typical clinical situation.)

$CTDI_{100}$: The CTDI with integration over a distance of 100 mm. (This definition facilitates determination of CTDI using a pencil-shaped ionization chamber having an active length of 100 mm.)

Note that the $CTDI_{FDA}$ and $CTDI_{100}$ are obtained by measurements made in standard acrylic phantoms. For $CTDI_{FDA}$ the absorbed dose is the absorbed dose in acrylic. For $CTDI_{100}$ the absorbed dose is usually expressed as absorbed dose to air at the location in the phantom.

$CTDI_{100,c}$ and **$CTDI_{100,p}$:** The $CTDI_{100}$ with integration over a distance of 100 mm where the subscripts c and p indicate the location, (x,y), within the CT dosimetry phantom for the measurement. The c and p indicate measurements made along the center axis or along a line near the periphery of the CT dosimetry phantom.

$CTDI_W$: The weighted $CTDI_{100}$, $CTDI_W$, represents the average of the $CTDI_{100}$ over all (x, y) positions in the CT dosimetry phantom used for measurement of dose. With the assumption that the dose in a phantom decreases linearly with radial distance from the surface to the center, $CTDI_W$ is defined as follows:

$$CTDI_W = \frac{1}{3}\, CTDI_{100,c} + \frac{2}{3}\, CTDI_{100,p}$$

$CTDI_{vol}$: The $CTDI_W$ defined previously estimates the average dose over the volume of the central slice when the scan increment I is equal to the slice thickness T. The $CTDI_{vol}$ is introduced to provide an estimate of the average dose over the volume imaged by a series of scans when the increment between slices is not equal to the slice thickness. This quantity can be defined for axial and helical scanning.

For axial scanning

$$CTDI_{vol} = \frac{nT}{I}\, CTDI_W$$

where T is the slice thickness, n is the number of slices obtained in a single axial scan, and I is the increment between scans of the series.

For helical scanning

$$CTDI_{vol} = \frac{1}{p}\, CTDI_W$$

where p is the helical scan pitch or pitch factor given by $p = I/nT$; and I, in this case, is the translation of the table during one rotation of the X-ray tube. With this definition, $CTDI_{vol}$ is the approximate average dose to the volume imaged during the series of scans.

Appendix 3 continues on the next page

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