Patient Dose From CT: A Literature Review

JOHN E. COLANG, M.S.R.S., R.T.(R), PMP
JEFF B. KILLION, PH.D., R.T.(R)(QM)
ELISEO VANO, PH.D.

Context *Computed tomography (CT) exams are increasingly common and account for a significant portion of individuals' mounting exposure to medical radiation.*
Objective *To explore issues surrounding patient radiation dose, including techniques for minimizing dose and the feasibility of tracking lifetime exposure to medical radiation from CT and other imaging exams.*
Methods *The authors conducted a review of the recent literature to assess current knowledge of dose levels, protocols for minimizing patient dose and possible systems for tracking cumulative dose.*
Results *Currently, no regulations are in place to track cumulative patient radiation dose. However, the authors discuss possible means of recording, tracking and storing this data, such as standardizing its inclusion in DICOM headers and transmitting it to electronic personal health records.*
Conclusion *More research is needed to develop and implement uniform dose tracking procedures and protocols for minimizing patient dose.*

As the number of computed tomography (CT) procedures performed in the United States continues to increase, there is growing concern about patient protection issues. Currently, no system is in place to track a patient's lifetime cumulative dose from medical sources, and questions have arisen regarding the possible threat to public health from the widespread use of CT, especially in pediatric patients.

The authors reviewed the published literature to determine whether patients are receiving a higher absorbed dose of radiation and explored several proposed models to optimize the radiation dose delivered to patients and track cumulative lifetime dose. The literature review was performed using various key scholarly databases and search engines. In an effort to limit the search to the most recent literature, only articles that were peer reviewed and published from 2000 to 2006 were selected for review. References to secondary sources were avoided whenever possible. For comparison purposes and to estimate the relative risk increase for stochastic effects such as cancer, patient doses are reported as "effective doses," which are measured in sieverts (Sv) in the International System of Units. Table 1 summarizes the key findings of this review.

Trends in Patient Dose

Physicians have come to rely on sophisticated imaging techniques to render more accurate diagnoses,[1] and CT has become the first-choice modality for many diagnosticians.[2] Scan times have been reduced, resulting in increased patient throughput and enhanced image quality.

A recent study by Aldrich and Williams[1] quantified changes in numbers of radiology exams at Vancouver General Hospital from 1991 to 2002 and examined the correlation to the radiation dose received by the patient. In addition to a 4-fold increase in CT exams, they also found that the average annual effective dose per patient almost doubled during the study period, from 3.3 mSv in 1991 to 6.0 mSv in 2002.[1] Other studies have described the average axial scanning effective dose for various regions of the body as 6.2 mSv.[3] Aldrich and Williams concluded that CT is the largest contributor to patient dose in radiology. This could be because more CT scanners are in use and their performance has been enhanced, along with increasing indications for CT exams.[1] In 2003 it was estimated that up to 29% of all CT units in the United States were capable of performing multidetector spiral scans, and it is likely that this number is much higher now.[3]

Table 1
Summary of Literature Review

Technical Factors:
Radiology departments should:
■ Focus on scanner protocols to reduce pediatric CT dose (mAs).
■ Use CT scanners with automatic exposure settings to limit dose.
■ Limit the region scanned to a minimum.
■ Adopt diagnostic reference levels.
■ Implement child-size guidelines.
■ Develop guidelines to compare dose indicators with standards.
■ Ensure that the indicator of CT dose (CTDIvol) is visible on the display console.
■ Include a DICOM file-format tag for CT dose information.
Educational Issues:
Imaging professionals should educate themselves on how to optimize exposure settings.
Patients should be informed of the risks of ionizing radiation from medical sources, but this should be balanced with an explanation of how benefits from CT scanning and other medical sources often outweigh risks.
Health care professionals must be prepared to discuss with parents why CT is sometimes the best exam to diagnose conditions in children.
Ordering physicians should be educated to request only necessary CT exams.
Emerging Trends:
Guidelines and standards are evolving that may lead to regulations for monitoring lifetime cumulative radiation dose from medical imaging sources.
More attention will be focused on cancer risks for pediatric patients undergoing multiple CT scans.
Additional support will go to CT research and clinical studies.
New government regulations are possible, with Europe leading the way.
ALARA (as low as reasonably achievable) will continue to be the goal.

CT is not the only modality that has experienced more use and has the potential to deliver higher patient radiation doses. Vano and Gonzalez studied radiation injuries from interventional fluoroscopic procedures.[4] Their study outlined possible root causes of radiation injuries from fluoroscopic procedures, including misuse, system faults and nonoptimized operational protocols. It drew attention to the fact that optimizing technique and standardizing practice could benefit the field of radiology and protect patients from overexposure to ionizing radiation. Although not pivotal to the discussion of correlating increased use of CT to an increased patient radiation dose, Vano and Gonzalez's study calls attention to the fact that dose to the patient can be reduced by careful attention to technique and optimization.

Yoshizumi and Nelson pointed out the need to balance optimization of image quality against radiation dose in developing clinical protocols.[3] Their study described fundamental concepts of radiation dose in detail, including the CT dose index and other technical factors such as pitch effect, dose profile in the penumbra and signal-to-noise ratio. Yoshizumi and Nelson concluded that multidetector CT (MDCT) radiation dosimetry issues have not been addressed adequately and have lagged behind advances in the actual technology.[3]

Other researchers also are questioning the effect of newer imaging technologies on patient radiation dose. Berland and Smith proposed that the absorbed dose could be up to 40% higher using MDCT compared with older generation scanners.[5] Golding and Shrimpton suggested that "evidence indicates a strong trend of increasing population dose owing to rising use of CT and to increased dose per examination."[6] A significant body of literature focuses on discovering a causal link between increased use of the CT scanner and an increase in radiation absorbed dose to the patient population.

Numerous studies have suggested that, although CT is not the most commonly performed radiologic examination, it is the largest source of radiation dose. Nagel et al found that, although CT represents only about 4% of all radiologic examinations, it is responsible for up to 35% of the collective radiation dose to the population

from radiologic examinations.[7] In a related National Cancer Institute report, data suggested that the use of CT in adults and children has increased approximately 7 fold in the past 10 years.[2] In large U.S. hospitals, CT represents 10% of diagnostic procedures and accounts for approximately 65% of the effective radiation dose for all medical examinations.[2]

Aldrich et al conducted a study to compare the dose length product and effective radiation dose to patients from CT examinations in British Columbia, Canada.[8] They compared data from 1070 CT exams and concluded that considerable variation existed in the dose length product and patient radiation dose for a specific exam. This study called attention to the need to optimize the effective dose to the patient and to conduct more research to determine which additional efforts are needed to minimize patient exposure. Optimizing technical factors for exams can help reduce the patient radiation dose, thereby reducing risks.[9,10]

A pivotal study by Lee et al assessed awareness levels among patients, emergency department physicians and radiologists concerning radiation dose and the risks involved with CT scans.[9] Lee and colleagues concluded that patients were not given information about the risks, benefits and radiation dose for a CT scan.[9] Regardless of their experience levels, few of the participants in the study (including the emergency department physicians and the radiologists) were able to provide accurate estimates of CT radiation doses. This study underscores the prevalent lack of attention to the issue of lifetime cumulative radiation dose. This must become a central issue so that risk can be studied and monitored. One disadvantage to communicating the risk of a cumulative radiation dose would be the natural instinct of some patients to defer or cancel the exam.[9] Professionals should highlight the benefits of the examination when discussing risks with the patient. Table 2 presents a list of questions and answers intended to help referring physicians improve their understanding of radiation risks from medical imaging exams.

CT Dose and Pediatric Patients

CT remains a very important modality for diagnosing disorders in pediatric patients. However, children are at a greater risk because they have a longer lifetime to manifest a radiation-related cancer. Frush et al drew interesting corollaries between the widespread use of x-rays in the early days of radiography, before the damaging effects of radiation were understood fully, and today's widespread use of CT on pediatric patients.[11] Frush and colleagues explored the risks of low-level radiation and CT[11] and advocated following the ALARA principle (as low as reasonably achievable). Their research suggested a statistically significant, increased risk of fatal cancer from low-dose radiation in the range of 50 to 100 mSv. "For example," they wrote, "a single CT of the abdomen could provide a dose of 11 mSv. If there are 3 phases in this examination, the actual dose is 33 mSv (3 x 11 mSv). If this child is 1 of the 30% who have 3 or more examinations, the lifetime dose is at least 100 mSv, clearly in the range of doses associated with induction of fatal cancer."[11] Table 3 lists some common pediatric CT exams and associated radiation doses.

Donnelly also drew parallels between the early decades of radiography and contemporary use of CT.[12] The author pointed out the increasing use and potential misuse of examinations, the lack of attention to dose risks, particularly in children, and the delay in implementing dose reduction strategies, all of which combine to form an interesting parallel to the early days of radiology. One fact emerges clearly throughout the body of knowledge in radiology: Attention must be drawn to the ALARA principle, especially where pediatric patients and CT are concerned.[2,11]

The National Cancer Institute suggested several steps to reduce the radiation dose to children.[2] First, only necessary CT examinations should be performed. Pediatricians and radiologists should consult to determine whether CT is the most appropriate examination. Second, if CT is the appropriate modality, exposure parameters should be adjusted to optimize the study and minimize the dose to the patient. Specifically, radiologic technologists should:

- Limit the region scanned to the smallest possible area.
- Optimize the mA settings for the organ systems to be examined (eg, lower mA for skeletal and lung exams).
- Adjust technique to the child's size and weight.
- Determine appropriate scan resolution (eg, a lower resolution may be sufficient for some diagnostic purposes).[2]

Physicians should minimize the use of multiple scans for contrast enhancement. Finally, radiology departments should develop pediatric CT protocols that describe these steps.

McLean also emphasized the importance of adjusting pediatric radiographic settings during CT to minimize dose.[13] McLean summarized optimization methods and suggested that further clinical studies be conducted on

Table 2
Questions and Answers To Help Physicians Understand Radiation Risks From CT

Why is an x-ray procedure, such as a CT examination, hazardous?	X-rays are high energy, ionizing radiation and will break apart DNA molecules. Light sources and microwaves have much lower energies, which are insufficient to break up molecules.
What are the hazards of x-rays?	The major concern from x-ray exposure is induction of cancer.
Is there a safe level of x-ray exposure?	There is no radiation exposure level below which the risk is zero. In general, the radiation risks are directly proportional to the amount of radiation absorbed by the patient.
How long does it take for a radiation-induced cancer to be expressed?	Radiation-induced leukemias have a latent period of a few years, whereas it takes decades for radiation-induced solid tumors to manifest.
Do radiation-induced cancers differ from naturally occurring cancers?	No, radiation-induced cancers can be detected only by epidemiological studies that compare an exposed group with a corresponding control group.
How does a chest CT examination compare with a chest x-ray examination?	The patient dose from a typical chest CT examination (5 to 10 mSv) is more than 100 times larger than a conventional chest x-ray examination (0.05 mSv).
How does a chest CT examination compare with natural, background radiation?	CT examination exposures generally are higher than 1 year's worth of background radiation exposure (~3 mSv).
What is the cancer risk for a patient undergoing a typical CT examination?	A CT scan with a dose of 10 mSv has an average cancer induction risk of about 1 in 1000, with half of those cancers being fatal (most are expressed decades after the scan).
Does the age of the patient at time of exposure affect the patient risk?	Definitely! Risks to children are about 3 times higher than those for a young adult. Risks to someone aged 50 years will be about 3 times lower than average.
Have CT examinations been shown to cause cancer?	No, as the overall cancer incidence is approximately 420 in a population of 1000; detecting a small excess (ie, 1 per 1000) would be difficult in an epidemiological study.
What factors should I consider prior to ordering a CT examination on a patient?	It is essential to balance the radiation risks with the corresponding patient benefits.
What are the general guidelines and policies for performing CT scans?	Eliminate unnecessary (nonindicated) examinations and ensure that no more radiation than is needed is used to perform an examination.
When is a CT scan indicated?	Patient benefits should be greater than the risks. Radiologists can advise on the risks and benefits of CT scans, as well as the use of nonionizing imaging methods.
How can patient radiation levels be kept as low as reasonably achievable (ALARA)?	Radiological studies should be tailored to specific clinical needs. For example, a chest CT exam to assess lung disease in a child with cystic fibrosis would need (much) less radiation.

Courtesy of Dr Walter Huda, Department of Radiology, Medical University of South Carolina, Charleston.

pediatric CT dose. Despite the overwhelming public health benefits of CT, McLean suggested implementing the following steps to protect an increasing population of children from cancer risks related to CT:

- Focus on scanner protocols to reduce pediatric CT dose (mAs).
- Use CT scanners with automatic exposure settings to limit dose.
- Develop guidelines to compare dose indicators with standards.

- Ensure that the indicator of CT dose (CTDIvol) is visible on the display console.
- Include a DICOM (Digital Imaging and Communications in Medicine) file-format tag for CT dose information.
- Emphasize education regarding CT protocols and dose implications.

Table 3
Approximate Radiation Dose by Pediatric Exam Type and Organ

Exam Type	Relevant Organ	Approximate Equivalent Dose to Relevant Organ (mSv)
Pediatric head CT scan unadjusted settings[a] (200 mAs, neonate)	Brain	60
Pediatric head CT scan adjusted settings[b] (100 mAs, neonate)	Brain	30
Pediatric abdominal CT scan unadjusted settings (200 mAs, neonate)	Stomach	25
Pediatric abdominal CT scan adjusted settings (50 mAs, neonate)	Stomach	6
Chest x-ray (PA/lateral)	Lung	0.01 / 0.15
Screening mammogram	Breast	3

[a] *"Unadjusted" refers to using the same settings as for adults.*
[b] *"Adjusted" refers to settings adjusted for body weight.*

The Profession's Position on Controlling Dose

Consensus in the literature reveals mounting concern regarding radiation dose in CT. This is reflected in international efforts to raise awareness about this issue. One group of scientists observed at a U.S. Food and Drug Administration science forum: "Our situation is given new impetus by new European and national regulations that require departments to introduce robust procedures for the protection of the patient, including the twin elements of ensuring clinical justification of the examination and optimization of the technique."[14]

In the United States, current practice does not include tracking the cumulative lifetime dose of ionizing radiation from medical imaging devices, nor are patients regularly informed of the risks of increased exposure to radiation from medical devices. However, this practice is beginning to shift in Europe, as evidenced by the European Council Directive that outlines steps to ensure that patients and practitioners are educated about the risks involved with radiation exposure, as well as steps to minimize the radiation dose to the patient.[14] The directive, 97/43/euratom, stopped short of mandating a record of the actual patient dose, noting that "Medical exposure continues to constitute the major source of European Union citizens' exposure to artificial sources of ionizing radiation. However, the use of ionizing radiation has allowed great progress in many areas of medicine. It is therefore essential that practices involving medical exposure are carried out in optimized radiation protection conditions."[14]

Similar efforts are underway in the United States to optimize procedures and thereby minimize radiation dose to the patient. Stern et al cited 9 proposed changes to the U.S. Performance Standard for Diagnostic X-Ray Equipment that will reduce unnecessary radiation emitted during fluoroscopy.[10] These are steps in the right direction but, like the European Council directive, fall short of fully regulating the measurement of patient radiation dose. A search of the literature did not reveal consensus among researchers regarding how these steps could be implemented in widespread practice.

The literature also underscores the need to develop and adopt reference dose standards for CT examinations. For example, Mayo et al found that large variations exist in technical factors used in pediatric chest CT.[15] They encouraged radiology departments to adopt reference dose value standards for these exams. Adopting these standards could benefit all patients undergoing CT exams.

The Role of Information Technology

Lacking in the literature is any mention of how the medical imaging community will implement a cradle-to-

grave radiation dose monitoring system. As discussion about tracking lifetime radiation dose from CT and other imaging modalities begins, a wide range of policy and technology changes will have to coalesce to develop the future model. First, government entities might consider including radiation dose in patients' permanent medical records. Second, radiology personnel, physicians, nurses and other allied health workers must receive education and training to understand the importance of good management of patient doses. Limiting lifetime patient cumulative dose should be a goal, with the understanding that occasionally there will be medical reasons to justify the use of a higher dose. Additional education and training will be needed to help health care professionals better inform patients of the risks involved. Finally, a partnership of technologies and standards will have to be formed to allow the practice to change.

As these changes find their way into the workplace, it will be necessary to develop a mechanism by which imaging equipment can transmit patient absorbed dose data to the radiology information system (RIS) or the picture archiving and communications system (PACS). Modern digital radiology equipment produces images with the dosimetric information contained in the DICOM header file. Vano et al pointed out that cooperation between the International Electrotechnical Commission and the radiology industry regarding standardization of the DICOM header will enable auditing of x-ray procedures and patient dose.[16] An immediate benefit of this effort would be automatic records that would reference comparison dose values and trigger an alarm if 1 of the monitored parameters was outside of an acceptable range.[16]

A review of the literature reveals a gap in how this information would be transmitted from the imaging device to a monitoring and archiving system. A possible model could include the RIS or the PACS transmitting the dose information to the personal health record, the enterprise health record or a regional health organization. At this point, the literature does not indicate which regulatory body would be the ultimate custodian of this data. A future model would need to describe how dose information from all medical imaging centers would be routed to a central data store for a patient. Careful evaluation and planning would be needed to provide a seamless transport conduit for these data. Health Insurance Portability and Accountability Act constraints regarding patient privacy could prove to be a challenge to implementing this model. Another possible constraint could be the cost of implementing a national model and developing a regulatory board to govern its policies.

One proposed model uses technology within the imaging device to transmit the dose information in real time to the PACS via DICOM using the modality-performed procedure step, or a newly proposed structured report within DICOM.[16] Important work has been done in this area by Vano et al, who suggested an online audit of the actual dose by comparing the dose to a diagnostic reference level.[17] "According to the International Commission on Radiological Protection, the average patient dose for a specific examination type should be compared with the diagnostic reference level for the examination."[16]

Vano and colleagues proposed a tool to identify any abnormal patient dose and determine the cause of the overexposure.[17] Their report describes the benefits and results derived from this model of online quality control. The authors proposed generating real-time alarms when baseline minimum doses were reached. In computed radiography, the exposure index would be audited. In interventional radiology, dose area product, number of images per series, total number of series and total number of images per procedure also would trigger an alarm if studies exceeded the baseline parameters. Additional research is required to determine whether real-time alarms for excessive doses are effective as an optimization technique.

DICOM Component

The DICOM standard was created by the National Electrical Manufacturers Association to enable transmission and viewing of medical images. DICOM has become the accepted conduit for transmitting medical image data throughout the world. Part 10 of the standard describes a file format for the distribution of images. Balter et al examined a variety of technical information describing image acquisition.[18] These data can be found in the DICOM headers of digital images. The authors described placing key exposure data in various public data elements and private fields. Because no standard currently exists, the exact location of this information depends on the manufacturer. Table 4 demonstrates an example of DICOM tags in the header of a generic flat panel. According to Balter and colleagues, efforts are underway to standardize the architecture for digital fluoroscopy: "A cooperative effort between the International Electrotechnical Commission and the DICOM committee is currently defining those dosimetric elements that should be stored for every examination

performed using 'digital' [sic] x-rays and its storage structure within DICOM public fields."[18]

Table 4
Sample Data From DICOM Tags in the Header of a Chest Flat Panel

(0008,0020)	Study date	7/01/03
(0008,0030)	Study time	10:31:12
(0008,0033)	Image time	10:32:43
(0010,0020)	Patient ID	NNNNNNN
(0010,0040)	Patient's sex	F
(0010,1010)	Patient's age	085Y
(0018,0015)	Body part examined	Chest
(0018,0060)	kVp	125
(0018,1150)	Exposure time	5
(0018,1151)	X-ray tube current	250
(0018,115E)	Image area dose product	0.83557
(0018,1190)	Focal spot(s)	0.6
(0018,1405)	Relative x-ray exposure	61
(0018,7060)	Exposure control mode	AUTOMATIC
(0018,7062)	Exposure control mode description	AEC_left_and_right_cells
(0028,0010)	Rows	2022
(0028,0011)	Columns	2022
(0028,0100)	Bits allocated	16
(0028,0101)	Bits stored	14

Downstream Data Repositories

Currently, there is no standard for acquiring, evaluating and archiving digital imaging data. Until a standard is implemented, important research needs to be done concerning prototype practice standards that permit dissemination of these data. Equipment manufacturers will need to reach consensus on a standard. Vano et al found that, at present, manufacturers of x-ray systems differ in how they populate the content of dosimetric information in the DICOM header.[16] Downstream data repositories could consist of RIS, PACS or any other subordinate system that would receive data from the modality. Dose data from the DICOM object could be transmitted electronically using a standardized format to a national data store or to a patient's personal health record or enterprise patient medical record. Figure 1 describes how image acquisition data could be transmitted to a national database or to RIS or PACS from the DICOM object.

Future Directions

A plethora of data implicates medical sources as the public's number 1 source of exposure to ionizing radiation. "In the 2000 report of the United Nations Scientific Committee on the Effects of Atomic Radiation, it was stated that medical applications of ionizing radiation represented by far the largest man-made source of ionizing radiation exposure."[19] Despite the fact that the benefits to the patient are enormous, lifetime cumulative exposure risks must be addressed. A search of the literature did not reveal any current requirements in the United States or Europe to track and monitor lifetime cumulative radiation dose to patients from medical imaging techniques such as CT and fluoroscopy. In the absence of requirements, a call is emerging for additional studies to describe the most efficient way to address this issue. The literature search did not reveal any effort to standardize key reporting variables in the United States, nor did it reveal consensus on efforts to standardize optimization methods and practices.

One important aspect in understanding dose reporting is that recording individual irradiation events is not sufficient for documentation purposes. Several regulatory bodies in different countries have recommended recording accumulated dose values such as the "dose at the reference point" or the "dose area product" per procedure. However, to complete dose reporting requirements, a distinct set of accumulated values must be provided to fulfill legal requirements for "recording of accumulated values applied during a procedure."[19]

Although definitions of diagnostic reference levels vary, they share common elements that include dose levels, standard-size patients or phantoms, dose quantity and specific equipment.[20] A recent article by Seeram and

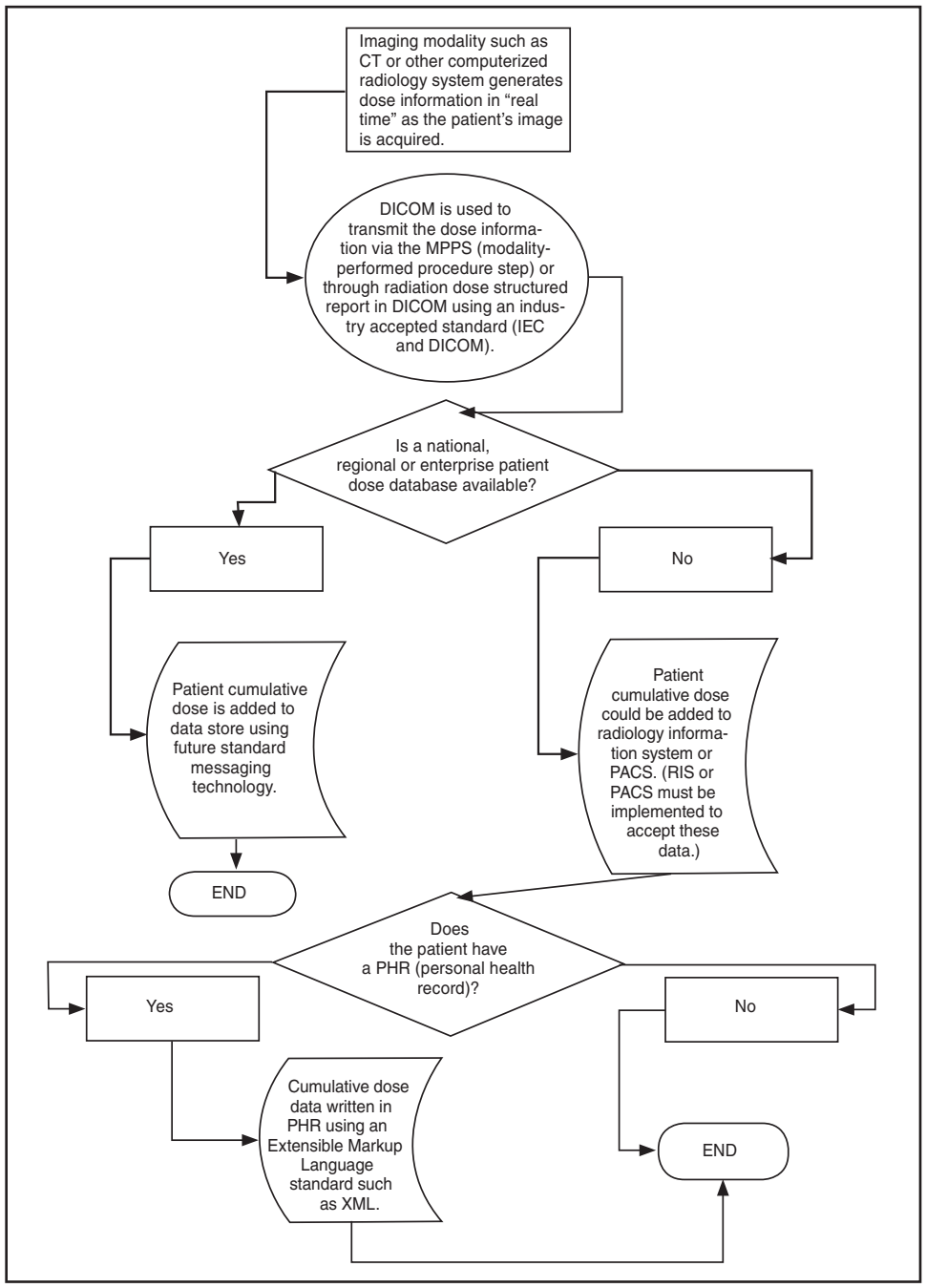

Figure 1. *Sample data flow from the CT scanner to a downstream data warehouse or personal health record.*

Brennan underscored the need for optimization and use of diagnostic reference levels (DRLs).[20] Their article focused on managing patient dose in diagnostic radiology by using DRLs, along with principles for optimizing radiation protection. DRLs must be relevant to the locale where they are applied and should be determined from radiation dose survey data.[20] The article discussed the 2 triads of radiation protection — principles (ie, optimization, justification and dose limitation) and actions (ie, time, distance and shielding). According to Seeram and Brennan, DRLs should be considered a dynamic parameter, and hospitals should perform regular dose surveys to ensure that levels remain applicable to new hospital equipment.[20] The authors suggested that a variety of parameters be examined when conducting a dose survey, including examination type, the number and type of hospitals involved, phantom and patient investigations, dosimetry methods, establishment of the reference level and accessory information.[20] Seeram and Brennan were careful to point out that, although optimization of the technique is an important step in limiting patient dose, care should be taken to ensure image quality remains high.

DRLs are a step in the right direction to standardize practice. The literature reveals that attention is beginning to focus on how radiology professionals could communicate and handle lifetime cumulative radiation dose from medical imaging devices. For now, Europe continues to lead the way in implementing a standard of practice for monitoring cumulative radiation dose from medical imaging. Supplement 94 of the DICOM Standards Committee, Working Group 6, Base

Standard, proposes a standard for capturing these data during image acquisition.[21]

Conclusion

The use of MDCT is on the rise and accounts for a large percentage of patient radiation exposure from medical imaging devices. A growing number of researchers in the medical imaging community are calling for heightened awareness of patient radiation dose from CT and other medical imaging radiation sources. Efforts are underway to examine methods and practices to allow the profession to reduce patient radiation exposure and track the lifetime cumulative radiation dose. Technical components will have to be standardized and implemented throughout the imaging community. Using DICOM as the principal transmission agent, a modality-performed procedure-step object or a newly proposed structured report template could be used to transmit patient radiation data downstream to a recipient PACS, RIS, personal health record, enterprise health record or yet-to-be-defined entity or object. Several technical and procedural issues remain and are not described fully in the literature.

In addition, further research is needed to determine the most appropriate method to develop and implement best practices that minimize exposure to patients by optimizing technical factors. More research also is needed on how to evaluate the efficacy of implementing a national radiation dose database to monitor a patient's lifetime exposure to ionizing radiation from medical imaging devices. Radiology professionals, as well as the general public, should educate themselves regarding the most effective ways to monitor patient cumulative radiation dose from CT and other medical imaging sources. In the interim, the focus should remain on optimizing image quality while conveying a minimal radiation dose to the patient.

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John E. Colang, M.S.R.S., R.T.(R), PMP, is a project manager for digital health projects with Intel Corporation in Albuquerque, New Mexico. Jeff B. Killion, Ph.D., R.T.(R)(QM), is an associate professor in the department of radiologic science at Midwestern State University in Wichita Falls, Texas. Eliseo Vano, Ph.D., is a professor of medical physics in the radiology department at Complutense University in Madrid, Spain.

Reprint requests may be sent to the American Society of Radiologic Technologists, Communications Department, 15000 Central Ave. SE, Albuquerque, NM 87123-3909.