CT Radiation Dose: What Can You Do Right Now in Your Practice?

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OBJECTIVE. The purpose of this article is to review reasonable measures that community radiologists can realistically implement as a response to the current increased public concern regarding CT radiation risk.

CONCLUSION. Potential measures include provision of patient information material, review of CT protocols and indications, promotion of alternative studies, use of decision support software, automatic tube current modulation, bismuth shields, improved image reconstruction algorithms, empowerment of technologists to adjust protocols, and calculation of radiation dose for possible reporting.

Public concern regarding health risks from ionizing radiation peaked in the early 1900s, when complications were first recognized in heavily exposed workers, and peaked again in the 1950s and 1960s at the height of the Cold War [1]. We now appear to be in another wave of radiation consciousness, as evidenced by publications suggesting that ionizing radiation from CT causes a substantial number of cancers [2, 3] and that CT radiation doses are unnecessarily high and variable [4]. These concerns have been compounded by widely reported gross errors in diagnostic and therapeutic radiation dose delivery [5, 6]. To some extent, the heightened radiation consciousness in North America reflects a transatlantic migration of radiation consciousness that has prevailed in Europe for many years [7]. Some of the more alarming recent claims are clearly suspect. For example, a projected lifetime attributable cancer risk of 1 in 80 from diagnostic CT only applied when the highest observed dose was delivered to a healthy 20-year-old woman [4]. Despite more reasoned responses to such selective data mining [8], the public concern remains heightened regarding radiation from imaging tests. We believe radiologists are best positioned to take the lead in responding. That being said, many community radiologists are uncertain how to address these concerns in their daily practice, particularly as MDCT technology has become increasingly powerful and complex. The purpose of this article is to review reasonable measures that community radiologists can realistically implement in their practices as a response to the current increased public concern regarding radiation risk. Many of the steps discussed reflect changes we have successfully introduced at our institution. The measures discussed deal primarily with CT, since CT is the single largest source of medical radiation delivered to the general population [9]. For descriptive purposes, these measures have been somewhat arbitrarily categorized as general measures and specific measures that can be taken before, during, and after a test (Table 1).

Provision of Patient Information Material

Ralph Waldo Emerson astutely noted, "Knowledge is the antidote to fear." Provision of clear and straightforward information for patients, either in a patient information leaflet or on a Website [10, 11], is a simple and effective first step in dispelling irrational or exaggerated fears of radiation. Radiologists still need to know a few critical facts about radiation risk so that they understand such material and can answer any residual patient questions. We regard the following as fundamental and useful data for handling such discussions.

Risk Must Be Balanced Against Benefit

Much of the recent publicity has focused on the cancer risks of medical radiation, and the widespread use of powerful modern technol-

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TABLE 1: List of Reasonable Measures Community Radiologists Can Realistically Implement in Their Practices in Response to the Current Increased Public Concern Regarding Radiation Risk

Category	Measure
General	Provide patient information material
	Review CT protocols and indications
Before the test	Promote alternative nonionizing studies
	Use decision support software
During the test	Modulate tube current automatically
	Introduce Bismuth shields
	Empower technologists to adjust protocols
	Improve reconstruction algorithms
After the test	Calculate radiation dose
	Report radiation dose

ogy capable of delivering increasingly higher doses of radiation does raise legitimate concerns. The risk must always be balanced against the unquestionable benefits of contemporary diagnostic imaging. For example, in a prospective study at Addenbrooke's Hospital in Cambridge, England, patients admitted because of severe abdominal pain were randomly selected to have a CT scan within 24 hours of admission or to have standard care. None of the 55 patients who got an early CT scan died, compared with seven individuals who died in the group of 63 patients who did not get an early CT scan ($p < 0.05$) [12]. Such studies indicate that the benefits of diagnostic tests using ionizing radiation are real.

All of Us Are Exposed Continuously to Radiation

All of us are exposed to radiation every day, mainly from the sun and soil. The entire body is exposed to this background radiation, whereas medical imaging studies typically expose only a portion of the body. The preferred method of measuring radiation dose in medical imaging is the effective dose (equivalent) measured in milliSieverts (mSv), which provides a conceptual whole-body dose that has the same risk as a dose given to just part of the body. For example, a brain CT scan is associated with an effective dose that is about 0.14 of the effective dose as the same amount of radiation used for an abdominal CT scan, because the brain is less radiosensitive. The small amount of background radiation we all receive annually is about 3 mSv [8]. The dose from a commercial coast-to-coast, round-trip airplane flight is about 0.03 mSv, which is equivalent to about 1% of annual background dose or two chest x-rays [13].

Radiation Doses From Most Medical Tests Are Small

The typical radiation doses associated with some common imaging tests are shown in Table 2 [13–17]. The table includes the equivalent period of background radiation for each dose, which is a practical and useful way of explaining dose to patients.

Risk Comparisons

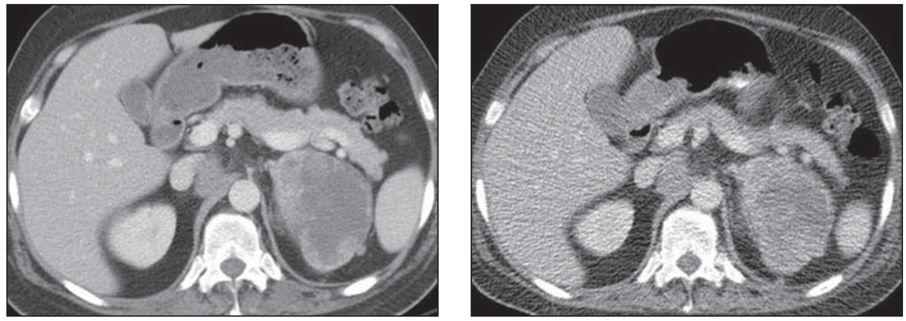
It is useful to remember some real-life comparisons when discussing a fatal cancer risk estimate of 1 in 2,000 for a dose exposure of 10 mSv. Such risks can be difficult for patients to understand, because "…for many, the only probability values they know are 50–50 and one in a million" [18]. Based on 2008 statistics [19], traveling 40,000 miles in a motor vehicle carries a 1 in 2,000 risk of accidental death. Obviously, this is a risk nearly all of us incur from our routine activities, and it is not a risk that generally causes undue anxiety or behavioral change. Another way of thinking about risk is to focus on the likelihood that something will not happen, rather than the odds that it will happen. For example, a 1 in 2,000 risk of cancer means a 99.95% chance of not getting cancer. This approach can substantially change how risk is perceived. For example, in a survey of 372 health professionals and 209 professionals in other fields regarding risk perception in the setting of prenatal screening [20], 16% reported they would be "very worried" if "told there was a 1% chance that your baby had a serious abnormality." When the same risk was presented as "How would you feel if you were told there was a 99% chance that your baby did not have a serious abnormality?" only 2% reported they would be "very worried."

Review CT Protocols and Indications

A simple step is to review existing CT protocols to ensure that radiation doses are as low as reasonably possible. For example, unenhanced CT for renal colic can be obtained with low-dose technique, because "noisy" images can still show urinary stones with high conspicuity. In addition to reducing the number of phases acquired and other high-level changes, the user can adjust the radiation output of the CT scanner through four scan parameters.

TABLE 2: Radiation Doses From Common Imaging Studies

Test	Dose (mSv)	Equivalent Period of Background Radiation	Reference
Chest x-ray (standard two views)	0.06–0.1	8–12 days	13, 14
Mammography	0.13–0.7	16–88 days	13, 14
Abdomen x-ray	0.5–0.7	62–88 days	14
Lumbar spine x-rays	1.8	7 months	14
Head CT	2.0	8 months	13
Chest CT	8.0	3 years	13
Abdomen and pelvis CT	10.0	3 years	13
Virtual colonoscopy	10.2	3 years	15
Whole-body PET/low dose CT	8.5–10.3	3 years	16
Whole-body PET/full dose CT	23.7–26.4	8–9 years	16
Prospective ECG-gated coronary CT angiography	3.0	1 year	17
Retrospective ECG-gated coronary CT angiography	11.7–13.0	4 years	17
Coronary angiography (diagnostic)	4.6–15.8	2–5 years	14
Coronary angiography (with intervention)	7.5–57.0	2–19 years	14



A B

Fig. 1—33-year-old man with primary adrenocortical carcinoma.
A, Axial 5-mm-thick, contrast-enhanced CT image obtained at 5-mm collimation and 440 mAs shows large necrotic mass in left adrenal gland.
B, Axial 5-mm-thick, contrast-enhanced CT image obtained in same patient 6 weeks later, inadvertently at tube current of 80 mAs, is grainier (noisier) but diagnostically adequate, and results in radiation dose 82% lower than CT technique used in **A**. Appropriate technical modifications can allow studies of similar diagnostic information to be obtained at lower radiation doses.

Maximum Tube Potential (kVp)

A higher kVp increases the flux and average energy of the x-ray spectrum produced by the x-ray tube and thereby increases, in an exponential fashion, the radiation dose. The tube potential setting for a standard diagnostic CT for an adult is usually between 120 and 140 kVp, owing to the need to adequately penetrate the mass of a large body. That is, lower kVp reduces dose but increases noise. More research is required to define the "sweet spot" at which dose is minimized while diagnostic image quality is maintained, but it is reasonable to use lower tube potentials (90–120 kVp) for children or smaller adults [21].

Tube Current (mA)

Radiation dose is directly proportional to tube current. In other words, doubling the tube current doubles the radiation dose. Lower mA studies are noisier but often allow diagnostically adequate images at a much lower dose (Fig. 1).

Table Speed (cm/s)

Radiation dose is inversely related to table speed. In other words, halving the table speed results in doubling the radiation dose.

Gantry Rotation Time

Radiation dose is directly proportional to gantry rotation time. In other words, doubling the gantry rotation time doubles the radiation dose.

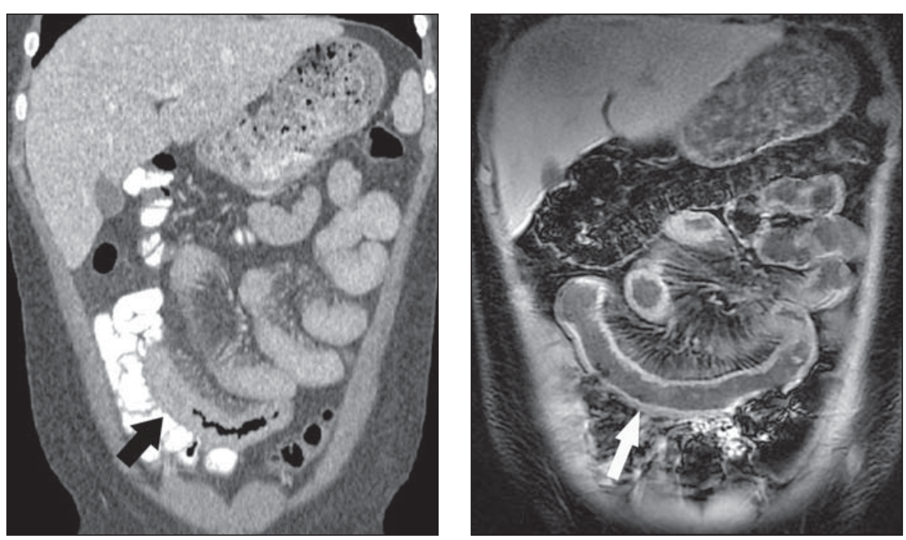
The initial focus should be on high-dose protocols, where dose reductions will be most substantial. For example, in a survey of 1,119 adult patients undergoing CT at four California Bay Area hospitals, the mean effective doses for a stroke CT and for a multiphase CT of the abdomen were 14 mSv and 31 mSv, respectively [4]. Described technical modifications for dose reduction during stroke CT include performing CT perfusion at 80 kVp and 70 mA, increasing time intervals between individual CT perfusion images, and using automatic dose modulation [21–25]. Methods of reducing the dose at multiphase abdominal CT include split-bolus technique for renal/hematuria studies, dual energy CT with creation of virtual non-contrast-enhanced images, and reduction of tube potential to 90 rather than 120 kVp for smaller patients [26–28]. The indications for multiphase CT studies should also be critically reviewed; a full multiphase study may be required at baseline for patients with suspected pancreatitis or pancreatic tumor, but follow-up studies may reasonably be limited to the portal venous phase. Given the complexity of modern MDCT technology, the expertise of a local medical physicist, if available, is useful in adjusting scan parameters to minimize dose consistent with the image quality requirements of the examination. For example, in consultation with our medical physicist, we recently implemented a variable kVp protocol such that patients weighing less than 100 lbs are scanned at 100 kVp.

Promotion of Alternative Nonionizing Studies

Although strategies to reduce dose are important, the optimum radiation dose is zero, making promotion of alternative nonionizing studies critically important. Some of the following suggestions may be challenging to implement for staffing or equipment reasons, but they are specific indications worth considering.

Use of MR Enterography Rather Than CT Enterography in Patients With Inflammatory Bowel Disease

These patients are often young, have a normal life expectancy, and receive multi-



A B

Fig. 2—12-year-old boy with known Crohn disease and increasing abdominal pain.
A, Coronal reformatted CT image shows thick-walled segment (*arrow*) of ileum with adjacent fatty infiltration.
B, Coronal gradient-echo, T1-weighted, gadolinium-enhanced, MR enterography image obtained 3 days after **A** shows similar findings, with segmental bowel wall thickening (*arrow*) and adjacent stranding. Greater use of nonionizing tests such as MRI could help reduce population radiation dose from CT.

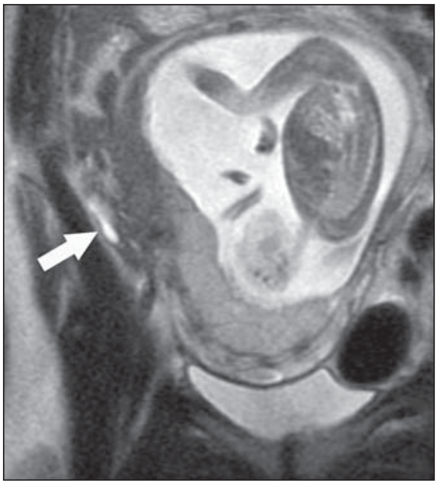


Fig. 3—33-year-old woman at 19 weeks gestation with acute lower abdominal pain. Coronal T2-weighted MR image shows a normal appendix (*arrow*). MRI is accurate alternative for imaging of suspected appendicitis in pregnant patients, because it eliminates CT radiation risk for both mother and child.

ple tests with ionizing radiation. In a review of 409 patients with Crohn disease seen at a tertiary European referral center, the mean cumulative effective dose of diagnostic radiation received was 36.1 mSv, and 15.5% of patients had a dose over 75 mSv [29]. With modern techniques, MR enterography is a robust alternative to CT enterography for these patients (Fig. 2) [30].

Use of MRI Rather Than CT for Patients With Suspected Appendicitis in Pregnancy

In the past, many centers performed CT for suspected appendicitis in pregnancy if an initial ultrasound was inconclusive. In the last decade, several reports have suggested MRI is an accurate alternative that eliminates the risk for both mother and child (Fig. 3) [31, 32].

Development of Referral Guidelines for Patients With Flank Pain

In a study at Duke University Medical Center, 79% of 356 patients with suspected renal colic had two or more CT scans [33]. The authors noted that radiation exposures from repeated CT scans are substantial, and a clinical decision rule for this scenario is needed. Certainly, the frequency of repeated studies is particularly disquieting, and it may be time to revisit whether ultrasound has a role in safely reducing the number of CT scans performed for flank pain.

Decision Support Software

Decision support software refers to computerized and automated provision of feedback in response to data entry by a clinical decision maker [34]. For example, in the setting of radiology, a physician electronically entering an order for a particular test may be given information on recent similar studies (to avoid unintended repetition) or a utility score reflecting the appropriateness of the test to the given indication [35]. In a preliminary study at Massachusetts General Hospital, the introduction of a decision support system reduced the percentage of examinations deemed “low utility” from 6% to 2%. Over time and with system improvements, such gains could be amplified and promote more rational use of imaging, in particular, studies using ionizing radiation. Of course, decision support software is only a practical option for practices with electronic order entry, but both electronic order entry and decision support software will undoubtedly become increasingly prevalent in the coming years. To ensure acceptance, decision support systems should be embedded in routine work flow and provide real-time, actionable, evidence-based, and up-to-date feedback [34].

Automatic Tube Current Modulation

Automatic tube current modulation refers to a system in which the CT tube current is automatically adjusted to the minimum level required to obtain a constant prespecified image quality according to the size and density of the tissue in the slice being scanned [36]. The adjustments are based on patient thickness and density from the scout images and can be made in both axial (x and y) and longitudinal (z) directions. Use of this “smart” technology can reduce radiation dose by 20–44% [36, 37], but a number of practical points should be remembered when using automatic tube current modulation.

The prespecified image quality metric becomes the primary determinant of radiation dose. The scanner will automatically adjust tube current to maintain the prescribed image quality even if other factors such as table speed or gantry rotation time are changed. For example, on GE Healthcare scanners image quality is evaluated by the noise index, which is a measure of the SD in the center of the field [38]. The operator sets the noise index. A higher noise index setting will give a lower radiation dose at the cost of a noisier image.

Do not use a high image quality metric for thin slices. Noisy (grainy) thin slices can be

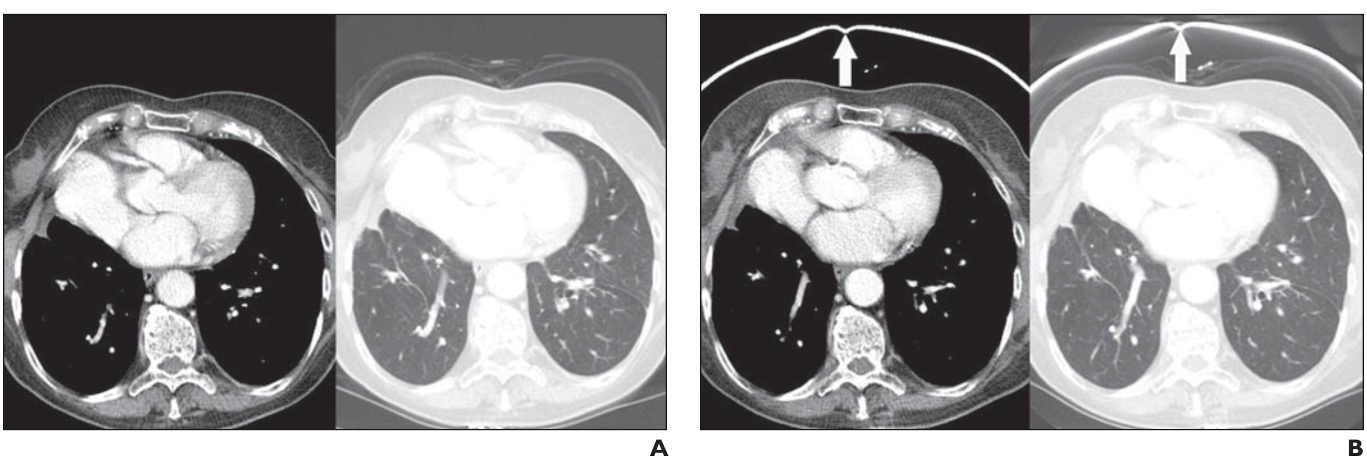


Fig. 4—75-year-old woman with history of right partial lung resection for cancer.
A, Photomontage of axial contrast-enhanced CT images of chest are displayed at soft tissue and lung windows.
B, Photomontage of corresponding images from subsequent CT obtained with bismuth shield (*arrows*) over breasts shows diagnostic quality of study unchanged, but dose to breast significantly reduced.

routinely reconstructed into thicker, less noisy images for interpretation (scan thin, reconstruct thick). Setting a low noise index for thin slices is particularly dangerous, because the radiation dose increases exponentially [39]. To get the same image quality at 1.25 mm as at 2.5 mm requires four times as much radiation.

The operator can typically set minimum and maximum tube currents to prevent over- or underexposure of the patient. Remember that high mA values or thresholds should not cause undue alarm when using 64-MDCT scanners, because these are generally offset by greater table speed. For example, radiation dose at 800 mA with a table speed of 55 cm/s is equivalent to that of 400 mA with a table speed of 27.5 cm/s.

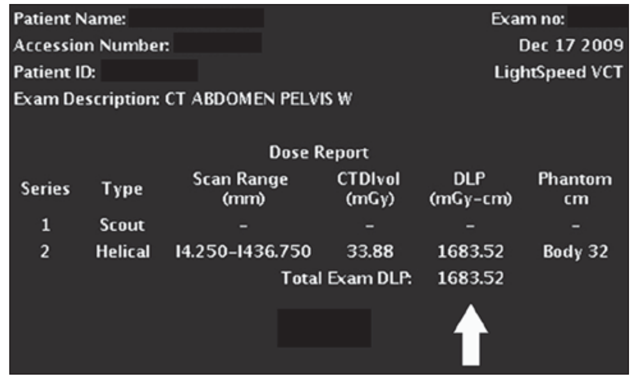


Fig. 5—Screensaver shows example of radiation report generated by modern MDCT and sent to PACS as separate series. Total dose-length product (*arrow*) is displayed in mGy/cm.

Bismuth Shields

Traditional radiographic shielding, such as gonadal shielding applied during an x-ray of the pelvis, works by nearly completely blocking the radiation beam. In-plane, bismuth shields for CT work by only partially blocking the beam. This casts a shadow and reduces the radiation dose to the underlying structure while maintaining image quality elsewhere. Bismuth shields are used primarily on the breast (Fig. 4), although they are also available for the eyes and thyroid. Clinical studies of bismuth shielding have shown a 29% decrease in radiation dose to the pediatric female breast [40] and a 40% decrease to the adult female breast [41], with no difference in noise or diagnostic quality. One concern when using bismuth shields is that automatic tube current modulation might offset the possible radiation reduction by increasing current to maintain photon flux through the shield. To prevent this, some have advocated that the shield only be applied after the scout view is obtained. A breast dose reduction of 52% was observed in a phantom model using bismuth shielding, irrespective of whether the shield was applied before or after the scout view [42], although the mean dose reduction across all sites was 46% when the shield was placed after the scout view versus 34% when the shield was placed before the scout view. Therefore, while either technique is an improvement over not shielding, it is preferable to shield after the scout view has been obtained. While the role of bismuth shields continues to be debated, we have successfully implemented a policy of routinely using bismuth breast shields on all women. Some practical problems can be easily addressed. Streak artifact may be seen if the shield contacts the skin, but the shields are generally supplied with a foam spacer that creates a step-off to prevent this problem. The shields are sold as single-use items, possibly creating a significant financial cost in a high-volume practice, but they can be reused if wrapped in a sheet or blanket to prevent skin contact. This wrapping has the added benefit of contributing to the air-gap needed to prevent streaking.

Empower Technologists to Adjust Protocols

A variety of CT Dose Index (CTDI) measurements have been described by regulatory and other agencies to quantify CT radiation dose. These measurements generally reflect the dose delivered to a standard phantom by a single axial CT acquisition. The $CTDI_{vol}$ is a further refinement developed by the International Electrotechnical Commission that accounts for helical CT [43]. $CTDI_{vol}$ is displayed before scanning a patient and is a measure of x-ray output for the technique factors (kVp, mAs and table speed) that will be used. Based on survey data obtained as part of the American College of Radiology (ACR) CT accreditation program, the ACR has established diagnostic reference levels for $CTDI_{vol}$ that approximately reflect the 75th percentile at ACR accreditation sites [44]. The ACR $CTDI_{vol}$ diagnostic reference level for a head CT is 75 mGy and for an abdominal CT is 25 mGy. CT technologists should be trained to check the projected $CTDI_{vol}$ for each study and should be empowered to adjust tube output downward or notify the supervising radiologist if the diagnostic reference level is going to be exceeded. Over time and with accumulated experience, it may be possible to reduce this upper limit for dose even further. Options to reduce output include increasing gantry rotation time, decreasing mA, lowering kVp, or setting a less demanding image quality metric. Experienced CT technologists can make significant dose-reducing modifications while maintaining diagnostic image quality. A noteworthy limitation of $CTDI_{vol}$ is that it assumes the scanner will operate at a constant mA and does not take into account changes in mA that occur when automated tube current (smart mA) is used.

Better Reconstruction Algorithms

Current CT scanners use filtered back projection for image reconstruction, but this method does not produce consistently diagnostic images at low tube currents. Iterative reconstruction is an alternative approach to image formation that uses an assortment of advanced mathematic models to correct and decrease noise in the image data so as to produce high-quality images at lower tube currents [45, 46]. Iterative reconstruction was used by the earliest CT scanners but requires prolonged computational times. A modified and faster version of iterative reconstruction known as adaptive statistical iterative reconstruction has recently become commercially available, and preliminary reports suggest CT dose reductions of 32–65% can be obtained while maintaining equivalent diagnostic image quality [45]. Unfortunately, this novel algorithm does involve a financial cost, because it requires software and hardware upgrades.

Calculate Radiation Dose

CT scanners record the radiation exposure as a DLP in mGy/cm. The reviewing radiologist can multiply this by the appropriate conversion factor to convert it to effective dose in mSv. Currently, the dose-length is typically saved on PACS within a radiation report that appears as a separate series in the form of a screensaver (Fig. 5). Conversion factors for obtaining effective dose from the DLP are shown in Table 3 [47]. In the absence of automated or computerized translation of DLP into effective dose equivalent, some rules of thumb may be helpful in calculating

TABLE 3: Current Conversion Factors for Obtaining Effective Dose From the Dose-Length Product

Body Part	Conversion Factor				
	Adult	10-year-old	5-year-old	1-year-old	Neonate
Head	0.0021	0.0032	0.0040	0.0067	0.0110
Neck	0.0059	0.0079	0.0110	0.0120	0.0170
Chest	0.014	0.0130	0.0180	0.0260	0.0390
Abdomen/pelvis	0.015	0.0150	0.0200	0.0300	0.0490

effective radiation dose in mSv. For brain studies, take 1% of the DLP and divide by 5. For example, a brain CT with a DLP of 2,523 mGy/cm gives an estimated radiation dose of 5 mSv. For body studies, take 1% of the DLP and add half of that figure. For example, an abdomen and pelvis CT with a DLP of 1,678 gives an estimated radiation dose of 25 mSv.

It is important to recognize that these calculations are approximations, not precise measures of an individual's radiation dose, so rounding to the nearest whole number of mSv is a reasonable approach. Reporting to two or more decimal places gives a false sense of precision. It should be noted that the conversion factors for calculating effective dose from DLP assume the patient is of standard size and do not account for individual variation from such norms, nor do they account for patient sex. Nonetheless, calculating CT radiation dose is an important exercise that raises radiation consciousness and allows early recognition of unusually high doses that may require protocol changes or educational feedback to technologists.

Report Radiation Dose

Including an estimated radiation dose and potentially the cumulative radiation dose in CT reports is a controversial suggestion because of the inherent errors in calculating dose and the dangers of causing anxiety or alarm for patients or their referring physicians. Arguably, dose reporting should occur only in conjunction with the provision of appropriate educational and informational resources for both patients and physicians [11]. Whether or not this approach is wise, it may well be the way of the future, given the contemporary focus on transparency, accountability, and patient empowerment. For example, the National Institutes of Health Clinical Center has started to routinely record CT and PET radiation dose exposure in the hospital-based electronic medical record, and these data are trackable by patients in their own personal health records [48]. An iPhone application, Radiation Passport, allows patients to track radiation exposure and calculate cancer risk related to their radiology examinations and procedures [49].

Conclusion

In conclusion, potential measures to address concerns regarding CT radiation dose that could be adopted right now in many radiology practices include provision of patient information material, review of CT protocols and indications, promotion of alternative nonionizing studies, use of decision support software, use of automatic tube current modulation, use of bismuth shields, empowerment of technologists to adjust protocols, improved reconstruction algorithms, and calculation of radiation dose for possible reporting. All of these measures may not be feasible for every practice. Some at least should be considered, however, as ways to counter the wave of alarm over the small and unproven risks of low-dose radiation that is sweeping the country and threatens to undermine the considerable benefits that accrue from the careful and judicious use of modern CT technology.

References

1. Brucer M. Radiation hysteria. *JAMA* 1961; 176:680
2. Brenner DJ, Hall EJ. Computed tomography: an increasing source of radiation exposure. *N Engl J Med* 2007; 357:2277–2284
3. Berrington de González A, Mahesh M, Kim KP, et al. Projected cancer risks from computed tomographic scans performed in the United States in 2007. *Arch Intern Med* 2009; 169:2071–2077
4. Smith-Bindman R, Lipson J, Marcus R, et al. Radiation dose associated with common computed tomography examinations and the associated lifetime attributable risk of cancer. *Arch Intern Med* 2009; 169:2078–2086
5. Bogdanich W. Radiation overdoses point up dangers of CT scans. *New York Times* Website. www.nytimes.com/2009/10/16/us/16radiation.html. Published October 15, 2009. Accessed September 14, 2010
6. Bogdanich W. Radiation offers new cures, and ways to do harm. *New York Times* Website. www.nytimes.com/2010/01/24/health/24radiation.html. Published January 23, 2010. Accessed September 14, 2010
7. Teunen D. The European Directive on health protection of individuals against the dangers of ionising radiation in relation to medical exposures (97/43/EURATOM). *J Radiol Prot* 1998; 18:133–137
8. AAPM response in regards to CT radiation dose and its effects. American Association of Physicists in Medicine Website. Updated December 16, 2009. Accessed September 14, 2010
9. Fazel R, Krumholz HM, Wang Y, et al. Exposure to low-dose ionizing radiation from medical imaging procedures. *N Engl J Med* 2009; 361:849–857
10. UCSF Department of Radiology and Biomedical Imaging. Computed tomography. www.radiology.ucsf.edu/patients/ct. Updated February 13, 2010. Accessed September 14, 2010
11. UCSF Department of Radiology and Biomedical Imaging. Radiation safety in the UCSF Department of Radiology and Biomedical Imaging. www.radiology.ucsf.edu/patients/radiation. Updated February 13, 2010. Accessed September 14, 2010
12. Ng CS, Watson CJ, Palmer CR, et al. Evaluation of early abdominopelvic computed tomography in patients with acute abdominal pain of unknown cause: prospective randomised study. *BMJ* 2002; 325:1387–1390
13. RadiologyInfo.org Website. www.radiologyinfo.org/en/safety. Accessed October 6, 2010
14. Health Physics Society Website. www.hps.org/documents/. Accessed October 6, 2010
15. Jensch S, van Gelder RE, Venema HW, et al. Effective radiation doses in CT colonography: results of an inventory among research institutions. *Eur Radiol* 2006; 16:981–987
16. Brix G, Lechel U, Glatting G, et al. Radiation exposure of patients undergoing whole-body dual-modality ^{18}F-FDG PET/CT examinations. *J Nucl Med* 2005; 46:608–613
17. Horiguchi J, Kiguchi M, Fujioka C, et al. Radiation dose, image quality, stenosis measurement, and CT densitometry using ECG-triggered coronary 64-MDCT angiography: a phantom study. *AJR* 2008; 190:315–320
18. Paulos JA. *New York Times* magazine, December 13th, 2009:20
19. National Highway Traffic Safety Administration Website. Fatality analysis reporting system. www-fars.nhtsa.dot.gov/Main/index.aspx. Accessed February 14, 2010
20. Abramsky L, Fletcher O. Interpreting information: what is said, what is heard—a questionnaire study of health professionals and members of the public. *Prenat Diagn* 2002; 22:1188–1194

21. McCollough CH. Automatic exposure control in CT: are we done yet? *Radiology* 2005; 237:755–756
22. Wintermark M, Maeder P, Verdun FR, et al. Using 80 kVp versus 120 kVp in perfusion CT measurement of regional cerebral blood flow. *AJNR* 2000; 21:1881–1884
23. Hirata M, Murase K, Sugawara Y, et al. A method for reducing radiation dose in cerebral CT perfusion study with variable scan schedule. *Radiat Med* 2005; 23:162–169
24. Smith AB, Dillon WP, Lau BC, et al. Radiation dose reduction strategy for CT protocols: successful implementation in neuroradiology section. *Radiology* 2008; 247:499–506
25. Mnyusiwalla A, Aviv RI, Symons SP. Radiation dose from multidetector row CT imaging for acute stroke. *Neuroradiology* 2009; 51:635–640
26. Chow LC, Kwan SW, Olcott EW, Sommer G. Split-bolus MDCT urography with synchronous nephrographic and excretory phase enhancement. *AJR* 2007; 189:314–322
27. Ho LM, Yoshizumi TT, Hurwitz LM, et al. Dual energy versus single energy MDCT: measurement of radiation dose using adult abdominal imaging protocols. *Acad Radiol* 2009; 16:1400–1407
28. Funama Y, Awai K, Nakayama Y, et al. Radiation dose reduction without degradation of low-contrast detectability at abdominal multisection CT with a low-tube voltage technique: phantom study. *Radiology* 2005; 237:905–910
29. Desmond AN, O'Regan K, Curran C, et al. Crohn's disease: factors associated with exposure to high levels of diagnostic radiation. *Gut* 2008; 57:1524–1529
30. Siddiki H, Fidler J. MR imaging of the small bowel in Crohn's disease. *Eur J Radiol* 2009; 69:409–417
31. Cobben LP, Groot I, Haans L, Blickman JG, Puylaert J. MRI for clinically suspected appendicitis during pregnancy. *AJR* 2004; 183:671–675
32. Pedrosa I, Levine D, Eyvazzadeh AD, Siewert B, Ngo L, Rofsky NM. MR imaging evaluation of acute appendicitis in pregnancy. *Radiology* 2006; 238:891–899
33. Broder J, Bowen J, Lohr J, Babcock A, Yoon J. Cumulative CT exposures in emergency department patients evaluated for suspected renal colic. *J Emerg Med* 2007; 33:161–168
34. Khorasani R. Clinical decision support in radiology: what is it, why do we need it, and what key features make it effective? *J Am Coll Radiol* 2006; 3:142–143
35. Rosenthal DI, Weilburg JB, Schultz T, et al. Radiology order entry with decision support: initial clinical experience. *J Am Coll Radiol* 2006; 3:799–806
36. Rizzo S, Kalra M, Schmidt B, et al. Comparison of angular and combined automatic tube current modulation techniques with constant tube current CT of the abdomen and pelvis. *AJR* 2006; 186:673–679
37. Kalra MK, Maher MM, Kamath RS, et al. Sixteen-detector row CT of abdomen and pelvis: study for optimization of *z*-axis modulation technique performed in 153 patients. *Radiology* 2004; 233:241–249
38. LightSpeed 7.X technical reference manual, direction 5116422-100, rev 2 (02/05). Waukesha, WI: GE Healthcare, 2005
39. Kanal KM, Stewart BK, Kolokythas O, Shuman WP. Impact of operator-selected image noise index and reconstruction slice thickness on patient radiation dose in 64-MDCT. *AJR* 2007; 189:219–225
40. Fricke BL, Donnelly LF, Frush DP, et al. In-plane bismuth breast shields for pediatric CT: effects on radiation dose and image quality using experimental and clinical data. *AJR* 2003; 180:407–411
41. Yilmaz MH, Albayram S, Yaşar D, et al. Female breast radiation exposure during thorax multidetector computed tomography and the effectiveness of bismuth breast shield to reduce breast radiation dose. *J Comput Assist Tomogr* 2007; 31:138–142
42. Coursey C, Frush DP, Yoshizumi T, Toncheva G, Nguyen G, Greenberg SB. Pediatric chest MDCT using tube current modulation: effect on radiation dose with breast shielding. *AJR* 2008; 190:W54–W61
43. International Electrotechnical Commission. Medical Electrical Equipment. *Part 2-44. Particular requirements for the safety of X-ray equipment for computed tomography*, 2nd ed. IFC publication number 60601-2-44 amendment 1. Geneva, Switzerland: IFC, 2003
44. American College of Radiology (ACR) practice guideline for diagnostic reference levels in medical x-ray imaging. 2006. www.acr.org/SecondaryMainMenuCategories/quality_safety/RadSafety/RadiationSafety/guideline-diagnostic-reference.aspx. Accessed April 24, 2010
45. Hara AK, Paden RG, Silva AC, Kujak JL, Lawder HJ, Pavlicek W. Iterative reconstruction technique for reducing body radiation dose at CT: feasibility study. *AJR* 2009; 193:764–771
46. Silva AC, Lawder HJ, Hara A, Kujak J, Pavlicek W. Innovations in CT dose reduction strategy: application of the adaptive statistical iterative reconstruction algorithm. *AJR* 2010; 194:191–199
47. American Association of Physicists in Medicine Report #96. Diagnostic Imaging Council CT Committee Task Group #23. The measurement, reporting, and management of radiation dose in CT. www.aapm.org/pubs/reports/RPT_96.pdf. Accessed September 14, 2010
48. Neumann RD, Bluemke DA. Tracking radiation exposure from diagnostic imaging devices at the NIH. *J Am Coll Radiol* 2010; 7:87–89
49. Baerlocher M. iPhone application tracks radiation exposure risk. Radiological Society of North America Website. www.rsna.org/Publications/rsnanews/December-2009/iPhone_feature.cfm. Accessed September 14, 2010

FOR YOUR INFORMATION

For more information on this subject and for practical steps to create a patient radiation safety program, see "For One Radiologist, CT Dose Safety is a Personal Matter," by Steven B. Birnbaum, in ARRS *InPractice*, Winter 2009, vol. 3, issue 2, page 30.