Cumulative Radiation Exposure and Cancer Risk Estimates in Emergency Department Patients Undergoing Repeat or Multiple CT

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OBJECTIVE. The purpose of our study was to define a conservative estimate of the number of patients undergoing repeat or multiple emergency department CT studies and to quantify their cumulative CT radiation doses and lifetime attributable risk of developing cancer.

MATERIALS AND METHODS. We identified all patients at a tertiary care adult academic medical center with at least three emergency department visits within a 1-year period that included CT of the neck, chest, abdomen, or pelvis. For this cohort, we identified all diagnostic CT studies over the previous 7.7 years. We calculated cumulative radiation doses by summing typical effective doses of the anatomic regions scanned, and we calculated lifetime attributable risk using the population-averaged dose-to-risk conversion factor of one cancer per 1,000 patients receiving a 10-mSv dose, in accordance with the seventh Biologic Effects of Ionizing Radiation (BEIR VII) report.

RESULTS. One hundred thirty emergency department patients met the inclusion criteria. Over the 7.7-year period, median, mean, and maximum values for the study count were 10, 13, and 70 with cumulative CT doses of 91, 122, and 579 mSv and lifetime attributable risk of one in 110, one in 82, and one in 17, respectively. Emergency department studies comprised 55% of those captured. Repeat imaging of the same study type represented at least half of the imaging for 72% of the cohort and all of the imaging for 12%.

CONCLUSION. A small proportion (1.9%) of emergency department patients undergoing CT of the neck, chest, abdomen, or pelvis have high cumulative rates of multiple or repeat imaging. Collectively, this patient subgroup may have a heightened risk of developing cancer from cumulative CT radiation exposure.

Keywords: CT radiation exposure, emergency department, radiation risks, repeat imaging

DOI:10.2214/AJR.08.1351

Received June 4, 2008; accepted after revision August 22, 2008.

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AJR 2009; 192:887–892

0361–803X/09/1924–887

In many ways, CT has transformed care for emergency department patients and is the technique of choice for a wide range of indications because of the timely and reliable diagnostic information it provides. The use of CT, particularly in the emergency department, has grown dramatically in the past decade [1–3], spurred by rapid technological advances, imaging speed, and widespread access to CT. This has heightened concerns about appropriateness, cost control, and resource utilization in both emergent and nonemergent settings. In addition, risks from cumulative radiation exposure have recently received more widespread attention [1, 2, 4–7]. Awareness of radiation risk is making its way into routine medical practice and may play a larger role in future utilization review and preapproval regulations [1].

Increased CT use has resulted in growing rates of repeat or multiple imaging in various patient populations. In 2002, Wiest et al. [8] found that 30% of all patients undergoing CT in their institution had more than three CT studies in their film jackets, 7% had more than five, and 4% had more than nine. Broder et al. [7] found that 79% of patients evaluated in the emergency department for renal colic underwent two or more CT scans. Jaffe et al. [9] reported that 9% of patients followed at their institution for Crohn's disease underwent more than five abdomen or pelvis CT examinations and 3% more than 10 examinations, nearly half of whom were imaged primarily in the emergency department.

Previous studies related to dose reduction and radiation risks have often focused on specific populations, such as pediatric patients or pregnant women, or on diagnostic imaging of particular organs [5, 6, 9, 10]. However, increases in usage and cumulative exposure observed more broadly in populations or settings such as the emergency department war-

rant further evaluation. Most emergency department practitioners will recognize a cohort of patients who, for various reasons, undergo recurrent CT on numerous visits. Although the impact and characteristics of frequent users of the emergency department have been previously characterized [11–15], data are limited regarding those undergoing frequent imaging and the associated radiation risks.

A recent American College of Radiology white paper includes many innovative suggestions for controlling radiation exposure, including development of "a surveillance mechanism to identify patients with high cumulative radiation doses due to repeated imaging" [1]. We sought to determine a conservative estimate of the size of this cohort undergoing repeat or multiple imaging studies from the emergency department, focusing specifically on CT involving tissues with the greatest risk of radiation-induced cancer. We estimated these patients' cumulative CT radiation doses and associated cancer risks from CT studies performed both from the emergency department and from all care settings combined.

Materials and Methods

Study Design and Setting

This retrospective, descriptive study took place for visits between June 1, 2005, and May 31, 2006, to an academic, adult, urban tertiary care, level 1 trauma center with 54,000 annual visits and an overall imaging density of 1.1 studies per visit. A dedicated emergency radiology section provides on-site attending coverage 24 hours a day every day of the year. There is currently a 64-multislice CT (MSCT) scanner, which replaced the previous 4-MSCT scanner in July 2005. Institutional review board approval was obtained for this HIPAA-compliant study, with informed consent waived for retrospective medical records review.

Patient Selection

Patient identification was done through a query of our radiology information system database (IDXRad, IDX Systems). To study a cohort likely to represent those undergoing repeat and multiple imaging and at elevated risk for radiation exposure to sensitive tissues, we identified all patients with at least three distinct emergency department visits within a 1-year period (June 1, 2005, through May 31, 2006) that included CT of the neck, chest, abdomen, or pelvis. Patients did not meet inclusion criteria if they had only two emergency department visits in 1 year in which they were imaged with CT or if they underwent multiple imaging on a single date (as for trauma). Previous studies have defined frequent users as those undergoing three to five annual visits [11, 14, 15]. We estimated that CT on at least three visits within 1 year would optimize sensitivity to capture those undergoing repeat or multiple imaging, without being overly inclusive.

TABLE 1: Typical Effective Doses Used

Anatomy	Effective Dose (mSv)
Head or face	2
Cervical spine or neck	2
Chest or pulmonary embolus	8
Abdomen	7.5
Pelvis	7.5
Ureter or abdomen–pelvis	15
Extremity	0.5

Measurements and Data Analysis

For each patient in the cohort, we tallied all CT studies performed in our hospital within a 7.7-year period from January 1, 1999, through August 30, 2006, representing the time period for which CT data were readily available. This included CT performed at our central hospital but did not capture CT performed at several affiliated inpatient and outpatient facilities, including an affiliated oncology hospital. Data analysis is descriptive.

We report the total number of patients in this cohort and summary data including the total number of studies performed, amount of repeat studies (defined as being the same study type), and cumulative dose and associated lifetime attributable risk stratified by location: all sites versus emergency department alone. In determining repeat studies, ureter CT was considered separately from general abdomen–pelvis CT because historically this study type has an independently elevated incidence of being repeated [6, 7].

CT Effective Doses Used

Effective dose, measured in sieverts, represents a whole-body equivalent dose that would be expected to produce the same overall cancer risk as nonuniform or partial-body irradiation. This dose is calculated as the sum of each organ's equivalent dose multiplied by a weighting factor that incorporates the relative risk of radiation-induced carcinogenesis in that organ. As a result, effective dose is commonly used as a convenient method to compare different exposures, even if they cover different anatomic regions [16].

Table 1 includes the effective dose values we used to calculate cumulative radiation doses. Relevant CT study codes were collapsed into seven anatomic regions, and each region was assigned an approximate effective dose value in millisieverts. These values reflect current typical adult dose estimates at our institution and fall within the range of published estimates [9, 17–23]. CT effective doses are highly dependent on patient size and on scanner parameters and technology. As such, Table 1 represents our best attempt to capture reasonable dose estimates for a typical patient in our setting. The values are supported by internal validation surveys of dose-length-product (DLP) for each common study type performed on our emergency department scanner (Sensation 64, Siemens Medical Solutions) and using standard methods to convert DLP to an approximate effective dose through use of body-region-specific conversion coefficients [24, 25].

To err on the side of underestimating exposure, CT studies involving multiple-pass scanning were assigned the same effective dose values as those with a single pass through the relevant body region. Cumulative effective doses were obtained by summing doses over each patient's CT study history.

Assigning Radiation-Induced Cancer Risk from CT Effective Doses

Longstanding controversy exists about the level of carcinogenic risk attributable to low-level ionizing radiation [26]. This is due in part to the epidemiologic challenges of studying rare events against a large background incidence of disease and the resulting need to extrapolate low-dose risks down from higher-level exposures at which causality has been shown. Controversy surrounds questions of an exposure threshold for carcinogenesis, of the linearity and slope of the dose–response curve, and of the effects of dose fractionation or of several small exposures in contrast to the single acute exposures that provide much of the available data from which the risk models are extrapolated.

Despite these controversies, the most widely accepted risk models estimate the lifetime attributable risk of radiation-induced cancer with a linear no-threshold dose–response curve [27–29]. For a given exposure, radiation risks are greatest in young patients because of both the intrinsically greater radiosensitivity of their organs and their longer remaining life expectancy during which a cancer may develop. The seventh Biologic Effects of Ionizing Radiation report (BEIR VII) predicts that for a standardized U.S. population, these age-dependent risks combine to produce an average lifetime attributable risk of one radiation-induced cancer per 1,000 patients receiving a 10-mSv effective dose; approximately half of these cancers are expected to be fatal [27]. This lifetime attributable risk is derived to reflect the expected additional cancer risk above the baseline cancer

TABLE 2: Summary Data for Individual Study Counts, Radiation Dose, and Associated Cancer Risk for the 130 Repeat or Multiply Imaged Emergency Department Patients

Source	Studies			Cumulative Dose (mSv)			Lifetime Attributable Risk		
	Median	Mean	Maximum	Median	Mean	Maximum	Median	Mean	Maximum
Total studies	10	13.4	70	91	122.0	579	1 in 110	1 in 82	1 in 17
Emergency department only	6	7.4	41	48	64.7	330	1 in 208	1 in 155	1 in 30

rate of 42% in the same standardized population [27]. For example, a lifetime attributable risk of one in 20 would reflect an increase in a typical patient's lifetime cancer risk from the baseline 42% up to 47%. It should be noted that because of multiple sources of uncertainty in deriving these risk models, the subjective confidence intervals for the BEIR VII lifetime attributable risk calculations vary by approximately a factor of two in either direction [27].

To estimate cumulative radiation-related cancer risks, we converted each patient's cumulative CT effective dose to estimated lifetime attributable risk using the standardized BEIR VII conversion of 0.0001/mSv. This is equivalent to summing the small cancer risks from each exposure, as described in chapter 12 of BEIR VII [27].

There are admittedly more involved approaches that further individualize patient-specific risk estimates by incorporating the patient's sex, age at time of each exposure, and the particular organs exposed [5, 10, 30]. However, the differential effects of such methods are expected to be small in comparison with the much larger underlying uncertainties of the BEIR VII risk model.

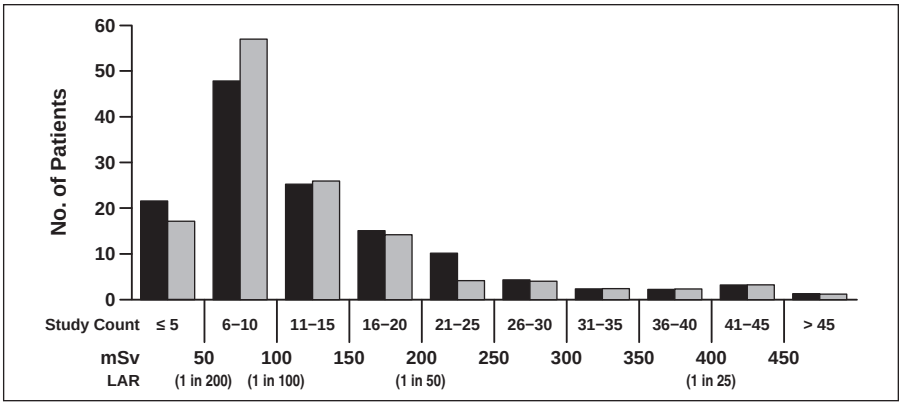

Fig. 1—Graph shows distribution of individual cumulative study counts and cumulative doses and lifetime attributable risk estimates. Black bars indicate histogram of cumulative CT study counts per patient during the 7.7-year study period. Gray bars indicate histogram of estimated cumulative effective dose (mSv) and estimated lifetime attributable risk (LAR) of developing radiation-induced cancer. Right-sided tails represent patients undergoing large cumulative numbers of CT studies and accruing high levels of cumulative dose and LAR.

Results

Patient Characteristics

During the index year, 10,009 unique emergency department patients underwent a total of 14,559 CT studies. Limiting these studies to the neck, chest, abdomen, or pelvis yielded 6,901 unique patients undergoing 8,827 studies. Five hundred twelve of these patients underwent at least three studies of these types on any number of dates, in part because of multiple imaging on the same date. Limiting the cohort to patients with at least one relevant CT study on three or more separate emergency department visits yielded 130 patients meeting inclusion criteria. Patients in this cohort were 63% women (82 patients) with a median age of 55 years and an average age of 56 years (age range, 21–95 years) There were 468 index-year studies of interest, distributed as 135 chest, 248 general abdominopelvic, 44 ureter, 36 neck, and five pelvis CT studies. The number of index-year studies per patient ranged from three to nine, with a median of three. Thus, the identified cohort represents approximately 1.9% (130/6,901) of the unique patients undergoing CT of the neck, chest, abdomen, or pelvis.

Distribution of Studies, Cumulative Doses, and Radiation-Associated Cancer Risk Estimates

Over the 7.7-year study period, our 130-patient cohort underwent 1,744 CT studies. Fifty-five percent (958/1,744) of these studies were performed in the emergency department. The number of CT studies, cumulative doses in millisieverts, and associated cancer risk estimates for emergency department and total studies are summarized in Table 2. Figure 1 contains the distribution of cumulative study counts and the associated cumulative dose and lifetime attributable risk estimates. Figure 2 contains the distribution of CT study categories performed in the emergency department and in all practice settings combined. In 72% of the cohort, at least half of the patient's studies were repeat studies. Figure 3 provides further detail on the mixture of repeat imaging (of the same study type) and multiple imaging of different types.

Discussion

More than half of the patients in the cohort underwent 10 or more studies and accumulated more than 91 mSv of cumulative radiation dose during the 7.7 years of available data, with an estimated lifetime attributable risk of developing a radiation-induced cancer of one in 110 or greater. The study that was by far the most often performed was abdominopelvic CT, followed by chest CT. The study most often repeated was abdominopelvic CT, followed by chest and ureter CT. Repeat imaging comprised more than half the studies performed in 72% of these multiply imaged patients and all of the imaging performed in 12% of these patients.

Our study focused on patients undergoing multiple or repeat imaging from the emergency department, although the approach can be generalized to any population. Our stringent threshold for inclusion into the study restricted our cohort to those we suspected to be at the highest risk because we sought to establish a conservative estimate for the size of this group and their associated risks of radiation-induced carcinogenesis. This group included 1.9% of all patients who met the clinician's threshold for ordering a CT study of interest during the index year. Their increased risk of carcinogenesis is reflected in estimated lifetime attributable risks ranging from one in 625 to one in 17.

The vast majority of emergency department patients, including many in our frequently

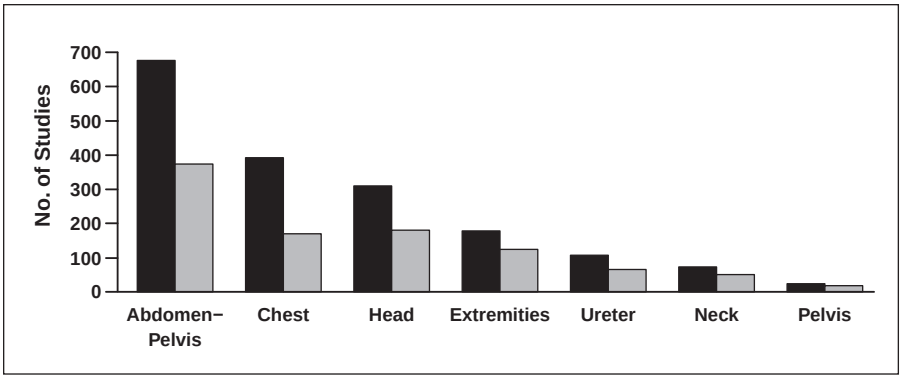

Fig. 2—Graph shows distribution of study types (all locations [*black bars*] vs ED only [*gray bars*]) during the 7.7-year study period. Fifty-five percent of studies were performed in ED.

imaged cohort, accrue small cumulative radiation doses and associated cancer risks. However, a small group of patients receive high levels of cumulative dose and estimated lifetime attributable risk from recurrent imaging. The BEIR VII risk model suggests the same marginal risk for an individual study regardless of a patient's imaging history. Nonetheless, for some frequently imaged patients, cumulative radiation risks may outweigh the aggregate historical benefits of the previous imaging. For subsequent presentations, the risk-to-benefit profile for some of these patients may justify the potential risks of no imaging or of imaging with a potentially less accurate alternate technique that delivers less or no ionizing radiation. Practical identification of these patients is best performed by inspection of an individual patient's comprehensive imaging history regardless of the practice setting. However, this patient history is not always readily available or easily retrievable in a usable format.

High-risk patients can be particularly challenging when presenting repeatedly to the emergency department with troubling complaints that have been repeatedly evaluated with no new findings but perhaps with previously confirmed disease that affects the decision to image yet again. Along with the occasional positive finding, this practice is also reinforced by the prevailing medicolegal environment.

Table 3 contains summary data for two example cohort patients. These vignettes highlight some of the complexities leading to repeat imaging and the challenges of reducing cumulative radiation exposure, potentially at the expense of diagnostic accuracy or physician confidence.

In the case of the frequent unchanged ureter CT studies in patient 1, a modified imaging approach is warranted using renal sonography as the first-line examination. Although sonography is more likely to provide false-normal findings in the setting of a small ureteral stone or a short time interval since symptom onset, both of these situations can arguably be managed conservatively in the absence of clinical concern for superimposed renal infection. When needed to guide management, hydronephrosis found at sonography may be followed by low-dose ureter CT to clarify the size and location of the offending stone. This and other proposed imaging algorithms for obstructive uropathy [6, 7] warrant more formal study. However, it seems reasonable that there will not be one single best imaging strategy for all patients but rather that stratification by cumulative radiation risk can play a role in adjusting the threshold for CT.

Patient 2 poses a different challenge in light of the potential morbidity of pulmonary embolus and the patient's history of venous thromboembolic disease. In particular, cumulative breast irradiation is the primary concern [31] and must be balanced against the patient's current clinical presentation. Parker et al. [31] have suggested that ventilation–perfusion imaging may be considered as a lower-dose alternative in a patient with normal findings on chest radiography, and in certain situations MR angiography may be considered to assess central emboli, although its accuracy remains limited for small emboli.

As in many areas of medicine, one size does not fit all, and diagnostic as well as therapeutic decisions should consider as much as possible the individual risk and benefit profiles for the patient at hand in context with the severity of the clinical presentation. Therefore, imaging decisions should consider not only a patient's pretest probability of disease but also the risks of the imaging itself, a task that has previously been difficult to assess on a patient-by-patient level.

Our study focused on cumulative CT exposures and associated radiation risks at a single urban academic emergency department, and generalization of results to other institutions would require similar CT availability and ordering practices.

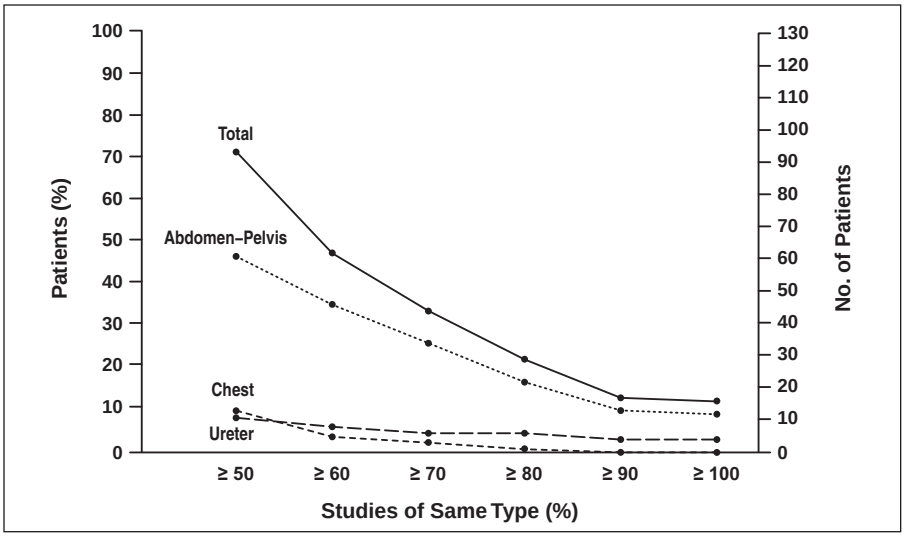

Fig. 3—Graph shows distribution of repeat study types per patient, plotting percentage (left *y*-axis) and number (right *y*-axis) of patients for whom more than *n* % of studies were of same type. Total curve shows that repeat imaging accounts for more than half of our patients' imaging in 72% of the cohort, and all imaging performed in 12% of the cohort. This is then subdivided into the three most common study types, with general abdomen–pelvis accounting for the majority of repeats. Each data point represents the proportion of each patient's study count originating from the most common study type, with the remainder including CT of other types.

TABLE 3: Example Clinical Vignettes

Parameter	Patient 1	Patient 2
Age and sex	44-year-old woman	43-year-old woman
Chief complaint	Numerous emergency department visits for flank pain	Recurrent chest pain, 113 emergency department visits in 8 years
Medical history	Recurrent pyelonephritis, previous lithotripsy and stone extraction, chronic microscopic hematuria, remote proctocolectomy for ulcerative colitis	Sickle beta-thalassemia, emphysema, hypertension, pulmonary emboli
Imaging history	Over 20 y (longer than study duration): 58 ureter CTs; 10 abdomen–pelvis CTs; one head CT; 12 IV pyelograms; four voiding cystourethrograms; four fluoroscopic renal interventions; three nuclear medicine studies; 55 abdominal x-rays; 40 chest x-rays; 19 other radiography studies; 62 sonography studies of abdomen or pelvis	Over 8 y (study duration): 19 PE CTs, two chest CTs, three abdomen–pelvis CTs, two maxillofacial CTs, two head CTs, one head and neck CT angiography, one ventilation–perfusion scan, 105 chest x-rays, one abdominal x-ray, five extremity x-rays, one shoulder MRI, five abdominal sonography studies
Cumulative CT effective dose	1,022 mSv	225 mSv
Estimated lifetime attributable risk	One in 10 (exceeds study maximum because of 20-y historical data collection)	One in 44
Imaging findings	One CT: 1-cm ureteropelvic junction stone, discovered after hydronephrosis at renal sonography; one CT: findings of pyelonephritis, concordant clinical presentation; all other CTs: incremental interval changes in size and location of nonobstructing renal stones	Six of 19 PE CTs: segmental or smaller acute PE; 13 of 19 PE CTs: chronic, decreasing, or resolved PE; multiple other CTs: incompletely occlusive superior vena cava thrombus at former port catheter tip

Note—PE = pulmonary embolus.

Because of our restrictive inclusion criteria, our estimates represent only the "tip of the iceberg" of cumulative CT exposures. For example, we did not include head CT in the inclusion criteria to avoid inflating the size of the cohort with patients primarily receiving recurrent head CT of relatively low effective dose. We expect that adding head CT to the qualifying studies would have increased the number of repeatedly imaged patients but shifted the distribution toward lower cumulative doses. Alternately, some patients multiply imaged in a single visit, such as for aortic dissection or multitrauma [4], have exposures that exceed the low end of our cohort's cumulative dose range.

Our study also captures only a portion of each patient's lifetime CT exposures because it includes a recent 7.7-year snapshot of data at our institution and does not capture studies performed at our affiliated cancer center, outpatient imaging centers, or other hospitals. Ultimately, a universal electronic medical record with access to all of a patient's historical sites of care would provide the greatest opportunity for accurate estimates of cumulative dose, but this degree of integration is not yet a reality.

Ideally, calculation of patient-specific cumulative doses would derive from a patient's actual exposures, incorporating patient size, the organs covered in the CT study, the CT technology used, and the specific imaging parameters used. For simplicity, we used typical effective dose values for CT of various anatomic regions. We could not derive them from each patient's actual exposures and did not attempt to incorporate changes in CT technology or protocols over the study period. As a general rule, our calculations assuming uniform CT technique and standard anatomic exposures will underestimate effective dose for small patients and overestimate effective dose for large patients [32]. It is hoped that CT manufacturers will soon begin to provide more accurate patient-specific doses as part of the archived information to aid future longitudinal dose monitoring efforts [33].

Our approximate conversions from cumulative dose to lifetime attributable risk use a standardized average risk of one in 1,000 per 10-mSv exposure. These methods may be further refined by incorporating the BEIR VII risk estimates stratified by patient sex and the age at each exposure. However, even in this case, inherent limitations of the BEIR VII approach will remain due to uncertainties in the low-dose radiation risk models estimated as a factor of two in either direction. In addition, at a patient-by-patient level, life expectancy must be considered in weighing radiation risks against the potential benefits of imaging. Because the BEIR VII models rely on typical life expectancies from actuarial tables, a given patient's predicted lifetime attributable risk must be adjusted downward if the patient's actual life expectancy is significantly shorter than age- and sex-matched peers.

Conclusion

A small cohort of emergency department patients undergoing CT accrue large cumulative radiation doses from frequent or recurrent CT both in the emergency department setting and overall, which may place them at higher risk for subsequent radiation-induced carcinogenesis. Individualized radiation risk assessment to identify and risk stratify such groups on the basis of cumulative dose estimates is one way of informing clinicians at the point of ordering how further imaging impacts the risk-to-benefit equation. At that point, recommendations for imaging with another technique or the use of established institutional protocols for addressing such scenarios may offer options to the clinician faced with the decision of whether to image again.

References

1. Amis ES Jr, Butler PF, Applegate KE, et al. American College of Radiology white paper on radiation dose in medicine. *J Am Coll Radiol* 2007; 4:272–284
2. Brenner DJ, Hall EJ. Computed tomography: an increasing source of radiation exposure. *N Engl J Med* 2007; 357:2277–2284
3. Broder J, Warshauer DM. Increasing utilization of computed tomography in the adult emergency department, 2000–2005. *Emerg Radiol* 2006; 13: 25–30
4. Winslow JE, Hinshaw JW, Hughes MJ, Williams RC, Bozeman WP. Quantitative assessment of diagnostic radiation doses in adult blunt trauma pa-

tients. *Ann Emerg Med* 2008; 52:93–97
5. Einstein AJ, Henzlova MJ, Rajagopalan S. Estimating risk of cancer associated with radiation exposure from 64-slice computed tomography coronary angiography. *JAMA* 2007; 298:317–323
6. Katz SI, Saluja S, Brink JA, Forman HP. Radiation dose associated with unenhanced CT for suspected renal colic: impact of repetitive studies. *AJR* 2006; 186:1120–1124
7. 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
8. Wiest PW, Locken JA, Heintz PH, Mettler FA Jr. CT scanning: a major source of radiation exposure. *Semin Ultrasound CT MR* 2002; 23:402–410
9. Jaffe TA, Gaca AM, Delaney S, et al. Radiation doses from small-bowel follow-through and abdominopelvic MDCT in Crohn's disease. *AJR* 2007; 189:1015–1022
10. Brenner D, Elliston C, Hall E, Berdon W. Estimated risks of radiation-induced fatal cancer from pediatric CT. *AJR* 2001; 176:289–296
11. Hansagi H, Olsson M, Sjoberg S, Tomson Y, Goransson S. Frequent use of the hospital emergency department is indicative of high use of other health care services. *Ann Emerg Med* 2001; 37:561–567
12. Mandelberg JH, Kuhn RE, Kohn MA. Epidemiologic analysis of an urban, public emergency department's frequent users. *Acad Emerg Med* 2000; 7:637–646
13. Sun BC, Burstin HR, Brennan TA. Predictors and outcomes of frequent emergency department users. *Acad Emerg Med* 2003; 10:320–328
14. Ruger JP, Richter CJ, Spitznagel EL, Lewis LM. Analysis of costs, length of stay, and utilization of emergency department services by frequent users: implications for health policy. *Acad Emerg Med* 2004; 11:1311–1317
15. Hunt KA, Weber EJ, Showstack JA, Colby DC, Callaham ML. Characteristics of frequent users of emergency departments. *Ann Emerg Med* 2006; 48:1–8
16. Brenner D, Huda W. Effective dose: a useful concept in diagnostic radiology. *Radiat Prot Dosimetry* 2008; 128:503–508
17. Conference of Radiation Control Program Directors, Department of Health and Human Services Website. Nationwide evaluation of x-ray trends: 2000 computed tomography. www.crcpd.org/Pubs/NextTrifolds/NEXT2000CT_T.pdf. Published April 2006. Accessed July 24, 2008
18. International Commission on Radiological Protection (ICRP). *Managing patient dose in computed tomography*, publication 87. Stockholm, Sweden: IRCP, 2000
19. United Nations Scientific Committee on the Effects of Atomic Radiation. *Sources and effects of ionizing radiation, 2000: report to the General Assembly with annexes*. New York, NY: United Nations, 2000
20. RadiologyInfo Website. Radiation exposure in x-ray examinations. www.radiologyinfo.org/en/safety/index.cfm?pg=sfty_xray#4. Accessed June 25, 2008
21. Cohnen M, Poll LJ, Puettmann C, Ewen K, Saleh A, Modder U. Effective doses in standard protocols for multi-slice CT scanning. *Eur Radiol* 2003; 13:1148–1153
22. Hurwitz LM, Yoshizumi TT, Reiman RE, et al. Radiation dose to the female breast from 16-MDCT body protocols. *AJR* 2006; 186:1718–1722
23. Mettler FA Jr, Huda W, Yoshizumi TT, Mahesh M. Effective doses in radiology and diagnostic nuclear medicine: a catalog. *Radiology* 2008; 248:254–263
24. Shrimpton P. Assessment of patient dose in CT, NRPB-PE/1/2004. Chilton, United Kingdom: National Radiological Protection Board (NRPB), 2004. Also published as Appendix C of the 2004 CT Quality Criteria at European Commission Website. www.msct.info/CT_Quality_Criteria.htm. Accessed January 2, 2009
25. European Commission. *European guidelines on quality criteria for computed tomography*, EUR 16262 EN. Luxembourg: Office for Official Publications of the European Communities, 1999
26. Brenner DJ, Doll R, Goodhead DT, et al. Cancer risks attributable to low doses of ionizing radiation: assessing what we really know. *Proc Natl Acad Sci USA* 2003; 100:13,761–13,766
27. Committee to Assess Health Risks from Exposure to Low Levels of Ionizing Radiation; National Research Council (U.S.). *Health risks from exposure to low levels of ionizing radiation: BEIR VII, phase 2*. Washington, DC: National Academies Press, 2006:xvi
28. International Commission on Radiological Protection (ICRP). *1990 recommendations of the International Commission on Radiological Protection*, publication 60. Stockholm, Sweden: IRCP, 1991
29. National Council on Radiation Protection and Measurements (NCRP). *Evaluation of the linear-nonthreshold dose-response model for ionizing radiation*, report 136. Bethesda, MD: NCRP, 2001
30. Brenner DJ, Elliston CD. Estimated radiation risks potentially associated with full-body CT screening. *Radiology* 2004; 232:735–738
31. Parker MS, Hui FK, Camacho MA, Chung JK, Broga DW, Sethi NN. Female breast radiation exposure during CT pulmonary angiography. *AJR* 2005; 185:1228–1233
32. Huda W. Radiation doses and risks in chest computed tomography examinations. *Proc Am Thorac Soc* 2007; 4:316–320
33. Brenner DJ, McCollough CH, Orton CG. Is it time to retire the CTDI for CT quality assurance and dose optimization? *Med Phys* 2005; 32:3225–3226

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 1, page 30.