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Title

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Permalink

<https://escholarship.org/uc/item/95r6r7mz>

Journal

Western Journal of Emergency Medicine: Integrating Emergency Care with Population Health, 13(2)

ISSN

1936-900X

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Publication Date

2012

DOI

10.5811/westjem.2011.11.6804

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Peer reviewed

Radiation Dose from Medical Imaging: A Primer for Emergency Physicians

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Supervising Section Editor: Michael Burg, MD

Submission history: Submitted May 24, 2011; Revision received July 31, 2011; Accepted November 9, 2011

Reprints available through open access at http://escholarship.org/uc/uciem_westjem

DOI: 10.5811/westjem.2011.11.6804

Introduction: Medical imaging now accounts for most of the US population’s exposure to ionizing radiation. A substantial proportion of this medical imaging is ordered in the emergency setting. We aim to provide a general overview of radiation dose from medical imaging with a focus on computed tomography, as well as a literature review of recent efforts to decrease unnecessary radiation exposure to patients in the emergency department setting.

Methods: We conducted a literature review through calendar year 2010 for all published articles pertaining to the emergency department and radiation exposure.

Results: The benefits of imaging usually outweigh the risks of eventual radiation-induced cancer in most clinical scenarios encountered by emergency physicians. However, our literature review identified 3 specific clinical situations in the general adult population in which the lifetime risks of cancer may outweigh the benefits to the patient: rule out pulmonary embolism, flank pain, and recurrent abdominal pain in inflammatory bowel disease. For these specific clinical scenarios, a physician-patient discussion about such risks and benefits may be warranted.

Conclusion: Emergency physicians, now at the front line of patients’ exposure to ionizing radiation, should have a general understanding of the magnitude of radiation dose from advanced medical imaging procedures and their associated risks. Future areas of research should include the development of protocols and guidelines that limit unnecessary patient radiation exposure. [West J Emerg Med. 2012;13(2):202–210.]

INTRODUCTION

Over the last 2 decades, a dramatic rise in the use of diagnostic computed tomography (CT) has led to concerns about increased cancer risks from cumulative exposure to ionizing radiation.^{1,2} Debate continues regarding the lifetime risk of fatal cancer imparted by any single imaging study or series of studies. However, several prominent regulatory and scientific societies state that no radiation dose is without carcinogenic risk.³

Although the American College of Radiology (ACR) and Society for Pediatric Radiology have addressed concerns regarding radiation dose with campaigns such as “Image

Gently” and “Image Wisely,” recent media reports of unnecessary exposure from CT have garnered national attention. One recent report found that 206 patients undergoing emergent “rule out stroke” CT protocols at a single hospital received up to 8 times the standard radiation dose for perfusion CT, which amounts to the equivalent of 200 noncontrast head CT.⁴ Such errors have prompted investigation by the US Food and Drug Administration (FDA) and calls for a framework to monitor radiology examination indications, dose delivery, and imaging history.⁵

As the volume of medical imaging obtained in the emergency department (ED) has increased over the last 2

decades, emergency physicians are now at the forefront of determining patients' exposure to ionizing radiation.⁶ Indeed, from 1995 to 2007 the number of ED visits that included a CT examination has burgeoned from 2.7 million to 16.3 million.⁷ Emergency physicians must be aware of risks inherent to ionizing radiation, available alternative imaging modalities, and appropriateness of each study. Currently, there are no review articles in the emergency medicine literature focused specifically on radiation dose in the ED setting. This article provides a general review of the current literature regarding radiation dose in the ED, highlighting recent efforts while also identifying areas for future research aimed at decreasing unnecessary radiation exposure in the emergency setting.

METHODS

We conducted a literature search for all journal publications regarding radiation dose from medical imaging in the ED setting in MEDLINE through calendar year 2010. Specifically, we performed a literature search for all articles with no limitations on date, type of journal article, or language by using the keywords "emergency medicine," "radiation dose," and several variations and combinations of the keywords. The first and last author independently reviewed 90 preliminary articles for relevance to the ED and radiation exposure from medical imaging. We included all articles pertaining to the level of radiation dose experienced by patients in the ED, the education or awareness of emergency physicians regarding radiation dose, and initiatives to reduce radiation exposure in the ED. We then reviewed all related citations for these preliminary articles that we deemed relevant, including all citations from the bibliography section of the selected articles.

To provide information specific to emergency physicians, we start with a brief, general overview of radiation dose terminology and then organize the results of our literature review into 3 commonly encountered clinical presentations for which medical imaging plays a major role in making the diagnosis in the ED: pulmonary embolism, renal colic, and recurrent abdominal pain in patients with inflammatory bowel disease. For each of these topics, we refer to ACR appropriateness criteria for medical imaging.⁸ We chose to exclude articles regarding radiation dose in trauma patients for whom rapid imaging likely outweighs the risks of radiation in most cases. We also excluded articles for the special cases of children and pregnant females for which discussion of radiation dose is beyond the scope of this general primer and would be more appropriately discussed in a separate article. Thus, for the purposes of our article we provide a literature review of specific clinical scenarios for adult, nonpregnant patients for whom action can be taken to decrease radiation exposure by avoiding equivocal or marginally indicated CT.

RESULTS

General Overview of Radiation Dose

Radiologic procedures that produce ionizing radiation include CT, plain radiography, nuclear medicine, and

fluoroscopy. The largest component of imaging-based radiation stems from CT, which is the focus of our article. Ionizing radiation causes damage at the cellular level via free radical formation, eventually leading to DNA mutation or cell death.^{9,10} Cellular mutations may eventually lead to radiation-induced cancers including leukemia, myeloma, or cancer of the thyroid, breast, lung, bone, and skin.¹¹

While the magnitude of cancer induction from any individual exposure to ionizing radiation cannot be measured exactly, the most widely accepted theoretical dose-response model is the linear no-threshold model.¹²⁻¹⁵ This model is an extrapolation of atomic bomb survivor data from Hiroshima and Nagasaki and is the most conservative, assuming even the smallest exposure to ionizing radiation has the potential to induce future cancer.^{16,17} The US National Academy of Sciences Biological Effects of Ionizing Radiation (BEIR) and the US National Council on Radiological Protection and Measurements both suggest the use of this model for estimating risks of ionizing radiation.^{11,18}

Several measurements are available for quantifying radiation dose. The quantity of ionizing radiation is measured in Gray (Gy) and is analogous to the older unit called a rad (radiation absorbed dose). Each radioactive particle—alpha, beta, and gamma rays (gamma is used in radiographs)—has a unique ionizing effect on biological tissue. This "equivalent dose" of gamma rays is expressed as the sievert (Sv) or rem (radiation equivalent in man). The conversion for radiographs is 1:1 such that 1 Gy of radiograph = 1 Sv (or 1 rad = 1 rem). Alpha and beta particles, emitted from a nuclear reactor or radiopharmaceutical, produce different effective doses and are beyond the scope of this review.

The term *effective dose* is widely used in the medical community and represents the weighted average of doses absorbed by irradiated organs, therefore reflecting the equivalent whole-body dose that would result in an equivalent risk from a nonuniform radiation source. It provides an estimate of a patient's risk of harm from any radiologic procedure, including all possible future cancers and hereditary effects. The effective dose allows for comparison across different imaging modalities and distributions across the body. However, the biological effect of radiation exposure varies substantially with age. It is most pronounced for young patients, whose organs are in closer proximity and whose cells are undergoing constant mitosis.

Moreover, the effective dose for radiologic studies can be considered in the context of normal annual background radiation for the general public. At approximately 3 mSv per year, the average background radiation from radon, cosmic rays, and other sources is not considered to be a significant cancer risk. For common radiologic procedures with an effective dose of 10 mSv (approximately equivalent to 1 CT of the chest, abdomen, or pelvis), the 2006 BEIR VII lifetime attributable cancer risk model predicts that 1 in 1,000 persons

Table. Average effective doses for common emergency department radiology studies.*

Procedure	Average effective dose (mSv)	Chest radiograph equivalent (PA and lateral)
Average background radiation exposure (per year)	3	30
Chest radiograph (PA and lateral)	0.1	1
Cervical spine radiograph	0.2	2
Thoracic spine radiograph	1.0	10
Lumbar spine radiograph	1.5	15
Pelvis radiograph	0.6	6
Abdomen radiograph	0.7	7
Hip radiograph	0.7	7
Shoulder radiograph	0.01	0.1
Knee radiograph	0.005	0.05
CT head	2	20
CT spine	6	60
CT stroke protocol (CT, CTA, and CTP)	14	140
CT chest	8	80
CT angiogram of thorax (rule out pulmonary embolism)	15	150
Lung V/Q scan	2.2	22
CT abdomen and pelvis	14	140
CT angiogram aorta (chest, abdomen, pelvis—rule out dissection or aneurysm)	24	240
Trauma CT “pan-scan” (head, neck, chest, abdomen, pelvis)	34	340

mSv, millisievert; PA, posteroanterior; CT, computed tomography; CTA, computed tomography angiogram; CTP, computed tomography perfusion; V/Q, ventilation-perfusion.

* Source: references 23 through 28.

will develop cancer due to such an exposure.^{18,19} Cumulative effective dose greater than 100 mSv from repeated exposures shows even more convincing evidence for increased cancer risk.^{1,20,21} A cumulative exposure of 1 Sv (1,000 mSv) confers a 4% to 5% increased relative risk of fatal cancer according to the International Commission on Radiological Protection.²² As discussed above, relative cancer risk varies with age, and, therefore, these estimates must be adjusted for younger and older patients accordingly.

We provide a table with average effective doses for common radiologic procedures ordered in the emergency setting (Table). This table is adapted from a number of recent reports in the medical literature and provides effective doses for adults.^{23–28} A recent study suggests that average effective doses may differ by up to 10-fold depending on specific imaging protocols and equipment settings.²³ Nevertheless, these doses allow for a general estimate of the risks associated with each type of study and can be used in helping to determine the risks in relation to the benefits of emergent radiologic procedures. Chest radiograph equivalents are also provided in the Table, which may be helpful in any patient-physician discussion regarding radiation dose from medical imaging.

Rule Out Pulmonary Embolism

Patients with suspected acute pulmonary embolism (PE) require rapid and accurate diagnosis to initiate anticoagulation. Workups for PE should begin with clinical risk stratification using standardized criteria. The Wells score and revised Geneva score are 2 commonly used prediction rules that can divide cases into high or low pretest probability of PE by risk factors and biomarkers.^{29–33} False-positive D-dimer test results in low-risk patients are common, however, and thus can lead to unnecessary CT if D-dimer testing is used for extremely low-risk populations. This problem prompted development of the PE rule-out criteria (PERC), which selects a population with low enough risk to not warrant D-dimer testing. PERC allows for risk stratification in which a negative score correlates with an acceptable, lower than 2% outcome rate of PE.^{34–36}

Posteroanterior and lateral chest radiographs serve as a useful screening tool that may reveal an alternative cause for pleuritic chest pain.^{37,38} If advanced imaging is necessary, CT pulmonary angiography (CTPA) of the chest has overtaken ventilation-perfusion (V/Q) scans as the modality of choice for suspected PE.^{39,40} The Prospective Investigation of Pulmonary Embolism Diagnosis II trial demonstrated that CTPA was more sensitive for detecting PE than V/Q scans, though the 2 modalities had similar positive predictive values.⁴⁰ The CTPA

technique has the added advantage of being able to identify alternative diagnoses such as aortic pathology, pneumothorax, or pericardial effusion.⁴¹

While CTPA is the imaging modality of choice, the total effective dose from CTPA is about 5 times greater than that from V/Q scans.^{25,42-44} Ventilation-perfusion scanning remains a valuable diagnostic modality in patients with contrast allergies, renal insufficiency, excessive obesity, and claustrophobia.⁴⁵ Unfortunately, V/Q scans are frequently indeterminate such that further diagnostic evaluation is often required. Indeterminate V/Q scans can be minimized by selecting patients who are young and have normal chest radiographic findings. Moreover, while fetal radiation is comparable between V/Q and CTPA, there is much less radiation exposure to radiosensitive breast tissue in pregnant females from V/Q scans than from CTPA.² Thus, V/Q scanning remains the primary modality for imaging female patients of child-bearing age with suspected PE and normal chest radiographic findings. Also, the dose of radiopharmaceutical in V/Q scans can be decreased by at least a factor of 3 with longer acquisition times in order to reduce radiation in pregnancy.⁴⁶

Renal Colic

Urolithiasis is a common condition that can lead to renal dysfunction if concomitant hydronephrosis is left untreated.⁴⁷ Imaging plays a role in the evaluation of suspected urolithiasis by demonstrating a stone's size, location, and effect on renal anatomy. Imaging can confirm the diagnosis and distinguish patients who need urologic intervention from those who do not. Moreover, an appropriate imaging study can also rule out more sinister etiologies of flank pain, such as renal cancer or nonurinary disorders such as appendicitis, diverticulitis, ovarian pathology, and abdominal aortic aneurysm (AAA).⁴⁸

CT is the modality of choice for evaluating adult patients with signs and symptoms of renal colic presenting for the first time.⁴⁹ A noncontrast CT of the abdomen and pelvis can quickly identify 95% of stones and rule out diagnoses such as appendicitis and AAA. Radiologists can also adjust certain parameters to reduce the effective radiation dose.^{50,51} These lower-dose protocols have effective doses as small as 1.5 mSv while maintaining high sensitivity and specificity.⁵²⁻⁵⁴ Recent studies have shown that low-dose CT stone protocols have the same sensitivity as usual CT for stones 3 mm or greater in size.^{51,55}

Some studies have suggested ultrasound (US) and magnetic resonance imaging (MRI) as alternatives to CT for renal colic.⁵⁶ However, institution-specific expertise and availability are limiting factors with both modalities. US of the urinary tract is highly operator-dependent, with sensitivity of US for acute flank pain reported at 61% to 93% and largely limited by poor visualization of the ureters.⁵⁷⁻⁵⁹ While plain radiography with US would greatly decrease radiation dose by an order of magnitude, sensitivity is lower than for CT.⁶⁰⁻⁶² This is why US leads to many equivocal studies for which CT may

ultimately be necessary.⁶³ Finally, although MRI can identify ureteral obstruction, its limited availability and suboptimal power to identify the cause and exact location limits its use.⁶⁴

Up to 50% of stone formers will suffer a recurrence within 10 years² and may undergo many CT.^{65,66} Katz et al⁶⁶ reported on the use of CT stone protocols for 4,562 patients during a 6-year period. They found that a single stone protocol CT imparted an effective dose between 6.5 and 8.5 mSv, with 4% of patients obtaining 3 or more CT examinations with a cumulative radiation dose between 10.5 and 153.7 mSv. In another study of 262 ED patients with renal colic who underwent CT, 92 patients had 3 or more studies within 10 months.⁶⁷ Repeated CT of chronic stone formers, compared to patients presenting with renal colic for the first time, has been shown to rarely change the diagnosis or treatment plan.⁶⁸

This population, thus, presents a dilemma to the emergency physician, who must weigh the risks of additional radiation from yet another CT against the risks of a missed alternative diagnosis or impassable stone. Combining US and kidney ureter bladder radiograph has been suggested as a first-line strategy for chronic stone formers with high pretest probability and low risk of other diagnoses.⁶⁶ Others feel that a patient with renal colic symptoms and a history of stones with a US finding negative for hydronephrosis or AAA can be discharged from the ED with putative treatment for uncomplicated urolithiasis.

Recurrent Abdominal Pain in Inflammatory Bowel Disease

Abdominal pain is the most common chief complaint in the ED associated with CT.⁷ Diffuse nonspecific abdominal pain results in fewer positive CT findings than localized pain, and may benefit from a period of observation.⁶⁹ However, no imaging substitute can effectively rule out a disease process with the sensitivity of CT, as evidenced by a 32% rate of positive findings in clinically ambiguous cases.^{69,70} In light of this, we advocate focusing dose-reduction strategies for patients with recurrent abdominal pain who are likely to undergo repeated CT, such as patients with inflammatory bowel disease (IBD).

IBD incidence peaks between 15 and 25 years of age, subjecting patients to a long period of remaining lifespan in which to manifest radiation-induced carcinogenesis.⁷¹ Moreover, IBD itself predisposes patients to gastrointestinal, liver, and biliary tract tumors.⁷² Recurrent flareups and complications such as strictures, fistulae, and abscesses lead patients to seek emergency care, with a high likelihood for obtaining repeated scans. CT utilization for such IBD complications has grown at a faster rate than other indications among the general population.⁷³ A study of 409 patients with Crohn disease found that 15% received a high cumulative effective dose (>75 mSv), a level of exposure that has been reported to increase cancer mortality by as much as 7.3%.⁷⁴

One alternative to CT for the IBD populations is US.⁷⁵ US has proved effective in detecting features of active IBD in

nonobese children, such as thickened bowel walls, hypoactive peristalsis, and increased mesenteric blood flow by Doppler.⁷⁶⁻⁷⁸ Bowel wall thickness greater than 2.5 mm in the terminal ileum or greater than 3 mm in the colon predicts active disease with 93% specificity.⁷⁹ Although 1 study suggested that US and CT had comparable diagnostic accuracy in identifying fistulae and abscesses in patients with IBD,⁸⁰ US in the setting of IBD remains highly operator-dependent, and sensitivity is variable between studies.⁸¹ Small-bowel obstruction, a common complication of Crohn disease, is best seen on CT rather than US.

MRI has gained increasing popularity in IBD evaluation. Active disease demonstrates thickened bowel that is enhanced on MRI with intravenous contrast.⁸² Compared to the gold standard of endoscopy or open surgery, these findings are more sensitive (92%) and specific (75%) than those of CT.⁸³ MRI can identify abscesses and fistulas as well.⁸⁴ Although availability and cost may limit use of MRI, its radiation-sparing effects are appealing.⁸⁵ Factors correlated with greatest risk for repeated imaging in patients with IBD include early age of onset, corticosteroid therapy, and need for multiple surgeries. Griffey and Sodickson⁸⁶ found that ED patients at 1 institution who underwent multiple CT had a mean cumulative radiation dose of 91 mSv and a lifetime attributable cancer risk of 1 in 110. These patients stand to gain the most benefit from choosing US or MRI over CT as the first line of imaging.

DISCUSSION

We have provided one of the first general overviews regarding radiation dose for the emergency medicine community and, to our knowledge, the first literature review regarding efforts to decrease unnecessary radiation exposure in the ED setting. It is obvious that CT imaging has had a transformative effect on emergency care by dramatically improving the speed and accuracy of diagnosis, thereby facilitating patient treatment and disposition. The explosion in CT utilization over the last 2 decades, however, has raised concerns about the deleterious effects of cumulative ionizing radiation. If current models of the carcinogenic risk imparted by low-dose radiation prove to be correct, CT may be contributing to a growing public health problem of radiation-induced cancers at the population level. Since ED physicians are ordering about one third of all CT studies in the United States, they must increasingly be knowledgeable about radiation dose and future radiation-induced cancer risks in their decision-making process, and possibly discuss these risks with their patients in cases for which the immediate benefits may not outweigh future risks.⁸⁷

On the basis of our literature review, we can conclude that there are 3 specific clinical scenarios among adults for which the ED physician should consider the risks of ionizing radiation from CT before ordering such studies, and for which alternative imaging modalities may be appropriate. These include ruling out PE, renal colic, and recurrent abdominal pain. While the available literature focuses on possible avenues for decreasing

radiation exposure in these specific situations, there is currently a paucity of rigorous and reliable protocols for ED physicians to follow in order to prevent unnecessary radiation exposure.

The most researched scenario for decreasing radiation dose to patients in the ED setting is the case of ruling out PE. A current review of the literature yields several steps that may help prevent unnecessary patient radiation exposure. First, standardized criteria for risk stratification should be used (eg, PERC rule or Wells score) for all cases. Second, an initial chest radiograph may reveal an alternative diagnosis and thus prevent the need for CTPA. Additionally, given its lower effective dose to the breasts, V/Q scanning should remain the primary modality for ruling out PE in pregnant patients and young women.

In recent years, abdominal pain has become the leading indication for CT in the ED, surpassing trauma and neurologic complaints.⁷ Unlike the case for PE, no established algorithms are in place to decrease CT studies among ED patients. Our literature review suggests that imaging abdominal pain varies with institutional preference, although centers with an interest in reducing radiation dose have developed low-dose CT protocols and the use of US as a screening tool for specific patient populations. Emerging studies suggest that low-dose CT protocols for renal colic may represent a compromise between risk of radiation and benefit of confirming the diagnosis of urolithiasis and possess equivalent sensitivity to standard CT.^{88,89}

More recently, chronic abdominal pain and IBD populations have been singled out as being at increased risk of radiation-induced cancer. Some experts have suggested that US be the initial study for patients with repeated IBD to assess for disease exacerbation. A diagnostic US study may obviate the need for CT, limiting repeated radiation to those with equivocal findings. MR enterography has become the imaging modality of choice for IBD in Europe, and advances in technique continue to drive adoption in the United States.^{84,90}

In addition to becoming familiar with radiation risks associated with common CT studies, emergency physicians should be aware of the risks associated with repeated scanning. A recent study that estimated cumulative radiation exposure from CT of adults in a tertiary academic medical center found that one third of all patients underwent 5 or more CT during their lifetime and that 15% of all patients had estimated cumulative effective doses greater than 100 mSv.⁹¹ Another study found that those who obtained repeated CT imaging from a single ED increased their risk of developing cancer from their repeated exposure, and that the same study type represented most repeated imaging.⁸⁶ Furthermore, Kline et al³⁴ determined that at least one third of ED patients who undergo CTPA to rule out PE will return for a second negative CTPA finding within 5 years.

As the public's exposure to radiation from man-made sources has become a national topic of interest and concern, more and more patients will likely want to discuss possible radiation-induced cancer risks with their ED physicians before

obtaining a CT. Moreover, as national governing bodies such as the FDA have classified ionizing radiation from medical imaging as a human carcinogen, patients are becoming more aware of the link between CT and cancer.^{92,93} The principles of medical ethics and patient autonomy dictate that ED physicians provide information regarding the risks, benefits, and alternatives of any given procedure to allow patients to make an informed decision.

Many physicians currently support the practice of obtaining informed consent for CT, including disclosure of minimal radiation-induced cancer risks.⁹⁴ If physicians do speak with patients about such risks, they should do so in language that is understandable by the average patient. For instance, the magnitude of average effective doses for a particular CT could be expressed in terms of number of chest radiographs, transcontinental flights, or additional days of background exposure.^{93,95} Furthermore, these risks should be expressed in light of the immediate benefits of obtaining a CT for any acute condition. It should also be stressed that any theoretic risk in increase of radiation-induced cancer from a single CT is actually a very small risk on top of the baseline cancer rate of 42% in the United States. For instance, since lifetime associated risk of fatal cancer from a single CT is estimated at around 0.1%, an abdominal CT effective dose is expected to increase the risk of developing cancer from 42% to 42.1%.²³

Concerns that patients will refuse necessary examinations because of irrational fear of developing cancer have not been borne out in practice. In fact, patients may prefer to confirm their diagnosis with CT despite the radiation risks involved.⁹⁶ Larson et al⁹² found that providing radiation-induced cancer risk information to parents of pediatric patients did not cause parents to refuse studies recommended by the referring physician. In another survey, nearly half of adult patients wanted to be informed about severe side effects with a 0.1% risk, whereas 13% of patients wished to be informed only when the risk reached 50% to 100%.⁹⁷

LIMITATIONS

As discussed in the “Methods” section, this literature review does not cover the pediatric and pregnant female populations. These special patient populations are outside of the scope of this general primer. Our article does not discuss technical aspects of CT, which we believe are best left to radiologists, radiology technologists, and radiation physicists. In addition, most of the literature regarding radiation dose outside of the ED setting was deemed to be outside the scope for this article. Our literature review was based entirely on a MEDLINE search, as no additional articles specific to radiation dose in the ED setting were identified from additional databases such as Cochrane Review and Google Scholar.

CONCLUSION AND POLICY IMPLICATIONS

While the ACR and similar organizations in Europe have developed appropriateness criteria for specific imaging studies,

the emergency medicine community has yet to become intimately involved. Since emergency physicians are now responsible for a large and growing percentage of the overall CT volume, ED governing bodies must work closely with the radiology governing bodies to further develop clinical algorithms and guidelines to streamline the most effective use of CT in the ED. Moreover, many current guidelines are not geared toward the ED setting and, therefore, are of limited use to the emergency physician.

Recent studies have shown that ED physicians and patients alike are largely unaware of associated radiation-induced cancer risks from CT.⁹³ Educational interventions may be effective for increasing such awareness. Stein et al⁹⁸ demonstrated that practice patterns of physicians changed in response to an educational intervention including the emergency, radiology, and nuclear medicine departments at 1 institution, resulting in a reduction in radiation exposure to ED patients with suspected PE without compromising patient safety.

Recently, California became the first state to require the reporting of radiation exposure for every CT performed after reports of recent higher-than-normal radiation doses from CT stroke protocols at several southern California hospitals. If more states follow suit or if there is eventual national legislation mandating such measures, ED physicians will be responsible for using dose-level information in their clinical algorithms for repeated CT imaging. Innovative research opportunities currently exist for the use of electronic medical records and computer-assisted physician order entry systems for helping to track radiation dose from imaging in the ED setting. In all of these future patient safety endeavors, emergency physicians will play a central role in minimizing unnecessary radiation exposure and they should be versed in discussing the topic with their patients, radiologists, and consulting physicians.

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Conflicts of Interest: By the WestJEM article submission agreement, all authors are required to disclose all affiliations, funding, sources, and financial or management relationships that could be perceived as potential sources of bias. The authors disclosed none.

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