Radiation Dose and Stochastic Risk From Exposure to Medical Imaging

The inscription on a medal given to me on behalf of the Cellular and Molecular Toxicology Division of Japan's National Institutes of Health Sciences 3 weeks before the September 11, 2001 terrorist attacks on the United States quotes Paracelsus (1493-1541): "All things are poisons, for there is nothing without poisonous qualities. It is only the dose which makes a thing a poison." Our ability to harness energy from radionuclides has resulted in enormous benefits, ranging from the generation of electrical power to the development of three-dimensional images of an organ. And yet these remarkable technologies have the potential for poisonous consequences. Exposure to a radiation dose of sufficient quantity leads to predictable cellular toxicities (ie, deterministic effects) such as apoptosis and necrosis, as well as to random events in cells that predispose to genetic mutations and malignant transformation (ie, stochastic events).

Radiation doses are measured as an absorbed dose (gray or Gy) in a material, or a dose equivalence (sievert or Sv) in a biologic tissue. One Gy is roughly equal to 1 Sv. Common prefixes include milli (10^{-3}) and micro (10^{-6}). For example, a milligray (mGy) is equal to 10^{-3} Gy, and a microsievert (μSv) is equal to 10^{-6} Sv. Doses from the 2011 Fukushima incident were extremely low and were, therefore, measured in μSv. The dose at which one-half of people die (lethal dose 50) at 60 days after exposure (lethal dose 50/60) for adults receiving supportive care plus antibiotics is 6.0 to 7.0 Gy (Sv). Aside from the psychologic and psychosocial impacts, the primary effect of low-dose exposure (generally considered to be <1 Gy or <1 Sv) is the induction of cancer.

The probability of cancer induction is related to radiation dose in a linear (for solid cancers) or curvilinear (for leukemia) fashion. Based on the evidence in the Life Span Study of Japanese atomic bomb survivors, such cancers will occur when the exposed individual reaches the age at which he/she is at risk of cancer at the site in question (ie, for breast cancer, it is after the age of 60 years old). Although the development of cancer is the most serious somatic effect of radiation at a dose of <1 Gy (<1 Sv), virtually all observational data have been derived from exposures to a dose of >0.1 Gy (100 mGy or 100 mSv).[1]

It is assumed that cancer risk at doses <100 mGy (<100 mSv) are also linear with dose, and that this risk declines as the dose reaches zero, without a threshold (ie, the linear, no threshold [LNT] model). Controversy exists regarding cancer risk at <100 mGy.[2] Results of laboratory studies often show minimal or no biologic effects at a dose of <100 mGy. Moreover, the LNT model for stochastic effects contrasts with the dose-effect relationship for deterministic effects in humans in which a threshold dose must be reached for deterministic injuries such as bone marrow depression, desquamation, mucositis, pneumonitis, pulmonary fibrosis, pericardial effusion and tamponade, esophagitis and stricture, hepatic fibrosis, venoocclussive disease, proctitis, cystitis, nephritis, and so forth. Therefore, the LNT hypothesis has not been validated by either experimental data generated in laboratory studies or observational data generated in epidemiologic studies. In fact, a dose threshold model (with a threshold value of 40 mGy, 95% CI, $<$0-85 mGy) for cancer incidence may fit the data as well as but no better than the LNT model.[3,4] If this threshold is applied, exposure to doses of <40 mGy would not result in a higher cancer risk.

To safeguard against radiation injury, the National Council on Radiation Protection and Measurements and the International Commission on Radiation Protection have developed recommendations for maximal permissible doses (MPDs) and dose limits based on the LNT model.[5] Table 1[1,6] provides a summary of the MPDs that are generally accepted by governments as maximal limits that are permitted by law. Both organizations recommend that radiation dose be kept as low as reasonably achievable (ALARA), "taking into account the state of technology and economics of improvement in relation to benefits to the public health and safety as well as inclusion of other societal and socioeconomic considerations."[7] The ALARA recommendation represents a conceptual approach that is based on continually evolving technology and economics.

In no other way has the recent change in average radiation dose to humans been affected more than by the development of body imaging. Although natural sources of radiation compose the major source of exposure in most countries, medical exposure has emerged as the primary source of exposure in the United States.[8] Diagnostic radiology and nuclear medicine examinations contribute 2.4 m Sv and 0.8 mSv, respectively, to the average annual exposure of 6.2 mSv. The largest contribution to exposure per study is the CT scan, with average effective doses of 14.0 mSv and 7.0 mSv for abdomen/pelvis and chest examinations, respectively. These doses may vary by up to 20-fold among patients receiving the same type of study, even within the same institution.[9] Owing to the rapid increase in the clinical use of CT scanning (estimated at an annual growth rate of 10% between 1993 and 2007),[8] the potential impact of this technology on overall cancer burden (and, therefore, health-care costs) is formidable.[9,10] The potential risk of radiation-associated cancer has led to calls for better regulation of the use

of medical imaging technology so that the benefit-risk ratio is maximized.[11,12]

The report by Rohner et al[13] in this issue of *CHEST* (see page 1481) addresses the radiation dose that occurs in a mixed-use, adult surgical ICU as a result of frequent diagnostic imaging. The authors calculated the effective dose for all diagnostic imaging studies performed on 74 consecutive patients. The effective dose takes into account the type (or quality) of radiation and the relative sensitivity of the exposed organ/tissue, as determined by the weighting factor for that organ/tissue. It is defined as the product of the equivalent dose in tissue and the tissue weighting factor summed over all tissues. It is useful for comparing studies and exposure types. For example, to compare the stochastic risk from a 4-mSv equivalent dose to the lung (whose weighting factor is 0.12) with a similar dose to the whole body, one multiplies 4 mSv by 0.12 to derive an effective dose of 0.48 mSv. Therefore, the risk from a lung dose of 4 mSv is about the same as a whole-body dose of 0.48 mSv.

The authors found that, in 6.8% of patients, the effective dose exceeded not only the public but also the occupational recommended dose limit of 50 mSv (see Table 1). The majority of the dose was due to CT scans. Accordingly, 6.8% of the patients discharged from this unit are at an increased risk of developing leukemia and/or a solid tumor as their attained age approaches the age at which these malignancies develop in unexposed individuals. The risk of incident cancers from CT scans has been estimated by the Biological Effects of Ionizing Radiation Committee to be 1.5% to 2.0%.[14] Cancer risk is higher in a child because of the increased number of years of expected life and the rapid growth of developing organs. Pearce et al[15] recently reported that the excess risk of leukemia and brain cancers may be tripled among individuals younger than 22 years of age whose cumulative dose from CT scans was 50 mGy (approximately 50 mSv), with an excess relative risk of 0.36 per mGy for leukemia and 0.023 per mGy for brain tumors. Although this study lacked a contemporaneous comparator group of unexposed individuals and it did not consider the precision of (or variability in) dose estimates, it provides, to the best of our knowledge, the first evidence that cancer risk may be increased after CT scans.

Table 1—*Recommendations for Maximal Permissible Dose*

Population	NCRP, mSv	ICRP, mSv
General public		
Annual MPD	1	1
Radiation workers		
Annual MPD	50	20
Cumulative MPD	10 × age (y)	NA
MPD during pregnancy	5	2

Modified from Mettler et al[1] and the ICRP.[6] Note: Government standards include maximal doses that are higher for occupational workers than for the general public, because radiation workers presumably accept a higher risk in exchange for the benefits of their employment. ICRP = International Commission on Radiological Protection; MDP = maximal permissible dose (effective dose limits for external exposure, exclusive of background radiation and medical radiation); NA = not applicable; NCRP = National Council on Radiation Protection and Measurements.

The "take home" message from the Rohner et al[13] study is that critical care physicians should carefully assess both the benefits and the risks before ordering diagnostic radiology examinations. Questions such as "does this study meet the guidelines for this condition," "how will this study improve patient care," "are alternative diagnostic approaches of equal benefit," and "is a radiology consultation indicated in this situation" should be answered before writing the order. These and other dose-reduction strategies have been reviewed by Sarma et al.[16]

In summary, much needs to be done to improve our understanding of a "safe" radiation dose. Although extrapolation of high-dose effects to the low-dose region (< 100 m Gy or < 100 mSv) of the dose-response curve may overestimate stochastic risk, it may be better to err on the conservative side when making recommendations of MPD to patients and/or their families. Following the principle of ALARA takes this uncertainty into account and allows physicians to accommodate new technology and fluctuations in health-care finances. Enhanced dialogue and enriched working relationships among epidemiologists and experimentalists will be important to clarify that which makes radiation a poison: its dose.[17]

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Financial/nonfinancial disclosures: The author has reported to *CHEST* that no potential conflicts of interest exist with any companies/organizations whose products or services may be discussed in this article.
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DOI: 10.1378/chest.13-1064

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OSA and Hypertension

Do We Know All the Answers?

There is accumulating evidence from well-designed, randomized controlled trials suggesting that OSA syndrome (OSAS) independently adds to cardiovascular risk. One major mechanism underpinning the association between OSAS and cardiovascular disease is likely to be sustained arterial hypertension, and this association may possibly be enhanced by frequent nocturnal acute BP rises. The repetitive episodes of obstructive apneas and hypopneas are often associated with arousals and intermittent hypoxia, both of which lead to increased sympathetic nervous system activity and consequent considerable transient increases in arterial BP up to 80 mm Hg. The activation of the sympathetic nervous system is also associated with an augmented production of catecholamines during the night, which are released into the circulation and may thereby contribute to the development of sustained arterial hypertension.[1] The nocturnal sympathetic nervous system activation, and consequently higher BP during sleep, may attenuate the advantageous physiologic dipping of BP normally seen at night. Augmented sympathetic activation in patients with OSAS has also been shown to be associated with impaired endothelial function, increased arterial stiffness, and blunted baroreflex sensitivity, which are contributing factors to the development of arterial hypertension.[1,2]

CPAP treatment has been shown to not only effectively abolish apneas, hypopneas, and oxygen desaturations, but also to prevent arousals and, thus, obviate acute BP rises. Several randomized controlled trials looking at the effect of CPAP on 24-h ambulatory BP have been conducted in the past decade; the results of these trials have established that CPAP treatment of patients with moderate to severe symptomatic OSAS lowers BP to a variable extent.[1,3,4] Most of the trials reported a reduction in BP of between 2 and 10 mm Hg after several weeks of CPAP therapy.[1,4,5]

The effect of CPAP therapy on BP in patients with OSA seems to depend on the severity of the sleep-disordered breathing, the presence of daytime sleepiness, and the extent of obesity, possibly the starting BP, and the hours of nightly CPAP use.[3,5,6] Studies suggest that, in symptomatic patients, the beneficial effects of CPAP on BP are found mainly in those who show good adherence to treatment (eg, >4 h per night), and this may also be true for patients without overt daytime sleepiness.[2,6,7] However, more evidence from well-designed studies is needed to answer questions such as the predictors of likely benefit and the hours of CPAP therapy necessary to achieve the full beneficial effect on BP. In all these studies there has been considerable interindividual variation in CPAP response, with some experiencing rises in BP rather than falls. This suggests that there may be opposing physiologic consequences of CPAP, with, for example, the loss of the nocturnal diuretic effect of OSA producing fluid retention and dominating over any reduction in sympathetic outflow.[8]

OSA has been proposed as a risk factor for resistant hypertension, which is defined as repeatedly measured BPs $\geq$140/90 mm Hg despite the use of three or more antihypertensive drugs of different classes. The prevalence of OSA (defined as an apnea-hypopnea index [AHI] of $\geq$10/h) has been estimated to be around 80% in patients with resistant hypertension, which suggests that there may be a causal relationship between OSA and resistant hypertension,[9] although the reverse could also be possible.

CHEST

Original Research

CRITICAL CARE

Cumulative Total Effective Whole-Body Radiation Dose in Critically Ill Patients

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Background: **Uncertainty exists about a safe dose limit to minimize radiation-induced cancer. Maximum occupational exposure is 20 mSv/y averaged over 5 years with no more than 50 mSv in any single year. Radiation exposure to the general population is less, but the average dose in the United States has doubled in the past 30 years, largely from medical radiation exposure. We hypothesized that patients in a mixed-use surgical ICU (SICU) approach or exceed this limit and that trauma patients were more likely to exceed 50 mSv because of frequent diagnostic imaging.**
Methods: **Patients admitted into 15 predesignated SICU beds in a level I trauma center during a 30-day consecutive period were prospectively observed. Effective dose was determined using Huda's method for all radiography, CT imaging, and fluoroscopic examinations. Univariate and multivariable linear regressions were used to analyze the relationships between observed values and outcomes.**
Results: **Five of 74 patients (6.8%) exceeded exposures of 50 mSv. Univariate analysis showed trauma designation, length of stay, number of CT scans, fluoroscopy minutes, and number of general radiographs were all associated with increased doses, leading to exceeding occupational exposure limits. In a multivariable analysis, only the number of CT scans and fluoroscopy minutes remained significantly associated with increased whole-body radiation dose.**
Conclusions: **Radiation levels frequently exceeded occupational exposure standards. CT imaging contributed the most exposure. Health-care providers must practice efficient stewardship of radiologic imaging in all critically ill and injured patients. Diagnostic benefit must always be weighed against the risk of cumulative radiation dose.** ***CHEST 2013; 144(5):1481–1486***

Abbreviations: ALARA = as low as reasonably achievable; LOS = length of stay; SICU = surgical ICU

Radiation exposure in US patients has doubled in the past 30 years[1] and can be attributed to a sevenfold increase in the use of radiologic imaging modalities.[2] Medical imaging now represents the greatest contribution to annual per-capita effective radiation dose in the United States.[1,2] Ionizing radiation damages DNA indirectly through free hydroxyl radical creation or through direct interactions with DNA,[3] and improperly repaired mutations can lead to cancer.[4] CT imaging continues to rise exponentially. Although no large-scale epidemiologic studies of cancer risk have been reported in association with CT scans, experts state that up to 2% of cancers in the United States may be attributed to radiation exposure from CT scans.[1] The

For editorial comment see page 1431

Manuscript received September 7, 2012; revision accepted March 1, 2013.
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Part of this article was presented in abstract form at CHEST 2011, October 22-26, 2011, in Honolulu, HI.
Funding/Support: The authors have reported to *CHEST* that no funding was received for this study.

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DOI: 10.1378/chest.12-2222

US government and the American College of Radiology have noted the dose increases and are formulating plans to track and regulate ionizing radiation exposure.[5,6]

One of the problems with radiation-induced cancer is the uncertainty about a safe dose limit. The National Council on Radiation Protection recommends the principle of keeping each patient's dose as low as reasonably achievable (ALARA), with the assumption that any radiation can cause detrimental DNA damage.[7] Whole-body effective dose (expressed in sieverts or millisieverts) takes into account all types of ionizing radiation to tissues and organs being irradiated and is weighted according to the ionizing radiation form and each organ's radiation sensitivity. Whole-body effective dose allows comparison of nonuniform exposure to the risk of a uniform whole-body exposure for all types of radiation. The Board on Radiation Effects Research VII[8] estimates that a population of individuals exposed to 100 mSv has a 1% increased risk of cancer during their lifetime. The International Commission on Radiologic Protection states that the maximum permissible dose for occupational radiation exposure is 20 mSv per year averaged over 5 years (100 mSv over 5 years) with no more than 50 mSv in a single year.[9] This contrasts sharply with public exposure, where 1 mSv per year averaged over 5 years is considered an acceptable limit.[10]

For perspective, Sarma et al[11] explained that over 1 year, individuals receive slightly less than one-half the dose (3 mSv) of a routine chest CT scan from background radiation and that driving 2,000 miles has a risk of a fatal accident similar to the risk of developing cancer from one or two CT scans. In 2006, the annual US individual radiation dose was 6.2 mSv of which 52% was from natural sources and the other 48% from medical sources.[12] CT scan contributed 24% to the total dose; nuclear medicine, 12%; interventional fluoroscopy, 7%; and medical and conventional radiography, 5%.[13]

The present study examined the typical radiation exposure to critically ill surgical patients during their surgical ICU (SICU) admission and to identify specific groups at increased risk for exposure exceeding US occupational standards. We chose the SICU because this population receives frequent medical imaging, allowing us to capture the higher end of exposure. We hypothesized that SICU patients would exceed 50 mSv. Specifically, we hypothesized that trauma patients would receive higher cumulative ionizing radiation doses than nontrauma patients.

Materials and Methods

The University of Cincinnati institutional review board approved this prospective, observational study (protocol #10071403). For 30 days, consecutive patients admitted to 15 predesignated beds were followed from SICU admission until SICU discharge or death. Patients who remained in the SICU past the 30-day study period were still followed until discharge or death. Pre-SICU imaging was included only for patients admitted directly from the ED and intraoperatively for scheduled direct SICU admissions postoperatively. CT imaging, fluoroscopy, nuclear medicine, and radiography were tracked. We included studies performed physically outside the unit during SICU admission. Ordering physicians were unaware of the study. Patient sex, age, height, and weight were collected. Patients were categorized as underweight (BMI $<$ 18.5), normal weight (18.5 $<$ BMI $<$ 24.9), overweight (25 $<$ BMI $<$ 29.9), or obese (BMI $>$ 30). Whole-body effective dose was calculated with methods developed by Huda and colleagues[14,15] (e-Appendix 1).

Statistical Analysis

Univariate and multivariable linear regressions were used to analyze the relationships between the observed values and the outcomes. An interaction term was used in the regression to assess the hypothesis that the relationship between length of stay (LOS) and total radiation was different in trauma vs nontrauma patients. Condition number, pairwise correlations, and variance inflation factors were calculated to detect multicollinearity. Regression diagnostics were used to assess the influence of individual observations. Statistical analysis was performed with R version 2.14.2 software (R Foundation for Statistical Computing).[16]

Results

Seventy-four patients were admitted to the predesignated SICU beds. Radiation doses did not differ by height, weight, age, sex, or BMI (Table 1). The median dose was 9.35 mSv (interquartile range, 0.18-27.4 mSv). Five of 74 patients (6.8%) accumulated $>$50 mSv of radiation (Table 2). CT scans accounted for only 20% of imaging but contributed 79% of the population's dose (Table 3). By univariate analysis, a trauma designation, LOS, number of CT scans, radiography, and fluoroscopy minutes were all significantly associated with a dose of $\geq$50 mSv. Multivariable analysis showed that the number of CT scans and fluoroscopy minutes were significantly associated with a dose of $\geq$50 mSv (both $P < .001$) (Table 4).

The mean LOS was 7 ± 8 days. LOS was not statistically predictive of increased radiation dose when controlling for the other predictors in the multivariable model. There were 27 patients admitted to the trauma service. A trauma designation was statistically significant in the univariate analysis ($P = .035$) but not in the multivariable analysis ($P = .571$). The interaction between trauma designation and LOS was statistically significant ($P = .035$), indicating that patients with a trauma designation had a slightly decreased total dose (-0.77 mSv) of radiation per day compared with patients without the trauma designation with the same LOS.

Discussion

We found that 6.8% of patients exceed the allowable annual US occupational radiation limit during their

Table 1—*Patient Characteristics*

Characteristic	Total Population (N = 72)	Total Dose < 50 mSv (n = 68)	Total Dose ≥ 50 mSv (n = 4)	*P* Value
Total dose	16.8 ± 22.9	12.2 ± 14.2	80.4 ± 26.5	< .001
Length of stay	7.4 ± 8.4	6.4 ± 7.4	21.4 ± 9.6	.003
No. CT scans	2.8 ± 3.8	2.4 ± 3.3	9 ± 6.1	.004
CT scan dose	13.3 ± 16.6	10.5 ± 12.8	52.3 ± 14.7	< .001
No. radiographs	10.6 ± 15.5	8.1 ± 11.8	44.4 ± 22.4	.001
Radiography dose	1.8 ± 2.8	1.3 ± 1.8	9.6 ± 2.9	< .001
No. fluoroscopies	0.6 ± 1.4	0.4 ± 1	4 ± 1.9	< .001
Fluoroscopy min	2.8 ± 14.6	0.8 ± 2.8	30.5 ± 52.1	< .001
Fluoroscopy dose	1.7 ± 8.9	0.4 ± 1.2	18.5 ± 32	< .001
Trauma	27 (37)	25 (36)	2 (40)	1.000
Length of stay > 7 d	20 (27)	16 (23)	4 (80)	.017
Baseline				
Age	53.7 ± 20.0	53.2 ± 19.9	61.2 ± 23.2	.489
Height	172.5 ± 13.7	172.1 ± 13.9	178.3 ± 11.0	.282
Weight	84.2 ± 22.3	84.1 ± 22.7	85.3 ± 17.8	.899
BMI	29.0 ± 12.9	29.2 ± 13.3	26.5 ± 2.7	.194
Female sex	30 (41)	28 (41)	2 (50)	1.000

Data are presented as mean ± SD or No. (%). *P* values are by *t* test, Fisher exact test, or Mann-Whitney *U* test, where appropriate. $P < .05$ is considered significant.

SICU admission. This finding is important because current evidence suggests that medical radiation dose and cancer risk are linear, even at doses < 50 mSv.[11] Our hypothesis that trauma patients would receive a higher cumulative dose than would nontrauma patients was rejected. Multiple studies have examined various aspects of medical radiation in specific subsets of patients, including dose, usage, risks, and benefits.[17-27] We were unable to find studies that reported a cumulative effective dose from all modalities in the general adult ICU population. Of note, no patients received nuclear medicine during their SICU stay. We set out to ascertain patients' cumulative effective dose and chose the SICU because this population receives frequent medical imaging, allowing us to capture doses in excess of 50 mSv.

Much of what we know about radiation-associated cancer is derived from the 1945 atomic bomb survivors in Japan, who experienced an acute, high-dose exposure (mean effective dose, 40 mSv).[1] These survivors are known to have an increased cancer risk, and it is feasible that similar radiation exposure can be reached with five to six CT scans. Medical radiation usually is delivered in a protracted course, so it is difficult to compare similar total doses to the acute exposure of the atomic bomb. However, patients may receive multiple CT scans in proximity (eg, a trauma series), which could have similarities to atomic bomb exposure. A small number of epidemiologic studies examined a more protracted exposure risk. A 2007 study in 407,391 radiation workers demonstrated an increased cancer mortality with increasing low-dose radiation over an extended period.[28] Furthermore, 146,022 radiology technologists who worked for ≥ 2 years had an increased risk for breast cancer and leukemia.[29] These protracted exposure studies suggest that patients are at increased risk for certain cancers from their cumulative medical radiation exposure. Although the risk of cancer from exposure to radiation doses of < 100 mSv is unclear, it has been suggested that a small, but significant increase in cancer risk, particularly in young and female populations, may be associated with exposure doses of 5 to 125 mSv.[11]

We defined 50 mSv as clinically significant on the basis of industry standards for occupational exposure[9] and hypothesized that some patients, especially trauma patients who received a full-body trauma series, would receive 50 mSv. Kim and colleagues[25] studied severely

Table 2—*Patient Imaging Modality Usage in Those Reaching 50 mSv*

Patient No.	Dose From CT Scans	Dose From Radiography	Dose From Fluoroscopy	Cumulative Effective WBRD	% of Dose From CT Scans	% of Dose From Radiography	% of Dose From Fluoroscopy	Service	LOS, d
1	50.14	12.07	6.44	68.65	73.04	17.58	9.38	ENT	27
2	47.38	8.33	2.09	57.8	81.97	14.41	3.61	Neurosurg	5
3	49.64	7.12	4.38	61.15	81.18	11.65	7.17	Trauma	24
4	76.95	13.35	4.03	94.33	81.58	14.15	4.27	Trauma	22
5	37.48	7.06	75.69	120.23	31.17	5.87	62.96	Transplant	29
Average	52.32	9.59	18.53	80.43	69.79	12.73	17.48	…	21.4

ENT = ear, nose, and throat; LOS = length of stay; WBRD = whole-body radiation dose.

Table 3—*Summary of Modality Use and Dose*

Modality	% Total Dose	% Total Imaging	Mean No. Studies Per Patient	Range No. Studies	Mean Dose, mSv	Dose Range, mSv
CT scan	79.2	20.1	2.81 ± 3.84	0-17	13.28 ± 16.62	0-76.95
Fluoroscopy min	9.9	4.5	2.82 ± 14.58	0-123.5	1.66 ± 8.85	0-75.69
Radiography	11.0	75.4	10.55 ± 15.51	0-70	1.84 ± 2.81	0-13.35

Data are presented as a summary of the key factors of each modality. Fluoroscopy results are reported in min for mean No. studies and range No. studies.

injured trauma patients with ICU stays > 30 days (mean, 2 months) and found that the cumulative dose per patient was 106 mSv. A 2007 study of 172 trauma patients used dosimeters placed on the neck, chest, and groin and found an average total effective dose of 22.7 mSv, but 22% of those patients received > 100 mSv to their thyroid gland.[27] We chose not to use dosimeters in the present study because this method may exclude exposure in the operating room as dosimeters cannot be placed in the sterile field. Additionally, dosimeters are prone to misplacement and require provider training and cooperation to ensure uniform results. However, these studies were helpful in comparing what a typical dose might be in the trauma population. Two of the five patients who reached 50 mSv during their SICU admission were trauma patients; however, our hypothesis that trauma posed an increased risk for doses exceeding 50 mSv was rejected ($P = .185$).

Regression diagnostics, particularly Cook's distance, indicated that there were two outliers. The first outlier received 123.5 min of fluoroscopy, totaling 75.69 mSv. This value accounts for a large mean and SD (2.8 ± 14.6) of fluoroscopy minutes in the data. Although the estimate of millisieverts contributed per fluoroscopy minute was highly influenced by this observation, fluoroscopy minutes remained a significant contributor to total radiation dose in the multivariable analysis. The second outlier had a 56-day LOS and a whole-body radiation dose of 44.4 mSv. The average LOS with the outlier was 7.4 ± 8.4 days and without the outlier, 6.4 ± 5.6 days; thus, LOS did not contribute significantly with or without the outlier ($P = .068$ and 0.290, respectively). Both outliers also influenced the estimate of the interaction between LOS and trauma designation. These outliers may not be representative of a typical ICU population.

Patients with more CT scans were more likely to receive 50 mSv of radiation. Excluding the fluoroscopy outlier, the four patients who reached 50 mSv obtained 73% to 81% of their exposure from CT imaging (Table 2). It is well recognized that CT imaging is a large contributor to overall population dose. Sodickson and colleagues[19] examined 22 years of cumulative CT scan dose and found individual doses up to 1,375 mSv. Furthermore, Smith-Bindman and colleagues[30] reported a 13-fold dose variation between different CT scans using the same protocol. As the largest contributor to dose, physicians must ensure that all CT scans are medically necessary, that equipment is maintained and calibrated, and that all protocols are carefully designed and monitored.

As with CT imaging, patients who receive increased fluoroscopy minutes were more likely to receive > 50 mSv. Each minute of fluoroscopy contributed 0.63 mSv of radiation, whereas each radiograph contributed only 0.25 mSv per study. Having an understanding of numbers like these might influence physicians' behavior on how early to use fluoroscopy to guide procedures. Frequent reminders in the operating room after an institutionally set time period can alert physicians to their usage (6 min of fluoroscopy equals the dose of about one CT scan). Hard stops in the ICU could also be set. Although conventional radiography studies were the most common (75%) imaging modality,

Table 4—*Predictive Variables in Increasing Effective WBRD in Univariate and Multivariable Linear Regression Analyses*

Covariate	Univariate Analysis		Multivariable Analysis	
	Estimate (95% CI)	*P* Value	Estimate (95% CI)	*P* Value
Trauma	11.62 (1.04-22.21)	.035	−2.17 (−9.75 to 5.42)	.571
Length of stay	1.77 (1.29-2.25)	< .001	0.7 (−0.05 to 1.45)	.068
No. CT scans	4.08 (3.07-5.09)	< .001	2.82 (1.9 to 3.74)	< .001
No. radiography	1.09 (0.86-1.32)	< .001	0.25 (−0.04 to 0.55)	.552
Fluoroscopy min	0.99 (0.71-1.27)	< .001	0.63 (0.41 to 0.85)	< .001
Trauma × length of stay	…	…	−0.77 (−1.48 to −0.06)	.035

Data are presented as estimate from univariate and multivariable linear regression, with effective WBRD as the outcome. $P < .05$ is considered significant. See Table 2 legend for expansion of abbreviation.

they contributed only 11% of radiation exposure. Studies have shown that routine daily chest radiographs can safely be eliminated in patients who are intubated, with no change in outcome.[20,21] Eliminating routine radiography and combining studies to confirm lines and tubes would reduce radiation exposure. Following the ALARA principle can decrease the cumulative dose patients receive from frequent radiography.

A limitation of this study is the small sample size of 74 patients. Individually measuring body part thicknesses from CT and other radiographic images was time intensive, so we were not able to expand the sample size. This was only an ICU study, and patients presumably received radiation after ICU discharge, making their total hospital stay dose higher than reported. Additionally, many patients received outpatient radiation for presurgical planning and for surveillance after hospital discharge.

The strength of this study is the mixed-use SICU that included general, trauma, transplant, vascular, thoracic, ear-nose-throat, trauma-neurosurgery, and urology patients, perhaps allowing the results to be generalized to the surgical population. The dose estimations were designed to account for radiography equipment and patient-specific factors and, therefore, are more accurate than generic estimations. The ordering physicians were blinded to the study.

The American College of Radiology,[31] the US Food and Drug Administration, and many experts in the radiation field have called for tracking total radiation dose in medical imaging. US radiation workers are allowed a maximum 50 mSv in a single year and the US public, 2% of that at 1 mSv. The radiation worker assumes increased exposure as a risk of the job. Yet, 6.8% of SICU patients in this study received the maximum allowable annual dose for US radiation workers in a much shorter time frame. There is no maximum dose limit for patients, but patients are reaching doses the US industry considers too high. Therefore, physicians must begin to think about the clinical application of a radiation budget, which we define as physicians ordering ionizing radiation testing in accordance with keeping the dose ALARA by forecasting the need for further imaging; eliminating unnecessary imaging; and considering nonionizing forms of imaging, such as ultrasound and MRI, when clinically applicable. This will require further physician education on radiation risk, quality control and assurance, training, and proper use.[32-34] A recent review on CT scanning[11] explained the dose with different CT scan modalities, dose reduction techniques, and optimization of use.

The present study indicates that patients from multiple surgical subspecialties are at risk for significant ionizing radiation exposure that can occur in only a few days and from different modalities. With electronic medical record implementation, institutions can offer physician reminders on the expected dose derived from a prescribed study, duplicative order alerts, and cumulative dose tracking. When all members of the care team are aware of the importance of radiation dose, radiation budgets can be crafted to minimize the cumulative effective of whole-body radiation dose and maximize diagnostic capabilities and patient safety.

Conclusions

In this prospective, observational trial in an academic medical center, 6.8% of an SICU population received more ionizing radiation exposure than the annual limit permitted for US radiation workers. Diagnostic benefit must always be weighed against the risk of cumulative radiation dose.

Acknowledgments

Author contributions: Dr Bennett had full access to all of the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis.
Dr Rohner: contributed to the study concept and design, data collection, and development of the manuscript.
Dr Bennett: contributed to the study concept and design and the development of the manuscript.
Dr Samaratunga: contributed to the study design, ionizing radiation source calibration, data analysis, and manuscript review.
Ms Jewell: contributed to the statistical analysis, interpretation of the data, and manuscript review.
Mr Smith: contributed to the ionizing radiation source calibration, data collection and organization, and manuscript review.
Dr Gaskill-Shipley: contributed to the study design and manuscript review.
Dr Lisco: contributed to the study concept and design and critical review of the manuscript.
Financial/nonfinancial disclosures: The authors have reported to *CHEST* that no potential conflicts of interest exist with any companies/organizations whose products or services may be discussed in this article.
Other contributions: This work was performed at the University of Cincinnati. The authors acknowledge Andrew Friedrich, MD, for his initial evaluation of statistical results; Cheri Fidh for tracking references; and Kevin Hatton, MD, William Hurford, MD, and Milo Engoren, MD, for reviewing the manuscript.
Additional information: The e-Appendix can be found in the "Supplemental Materials" area of the online article.

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