Radiation Dose Associated With Common Computed Tomography Examinations and the Associated Lifetime Attributable Risk of Cancer

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Background: Use of computed tomography (CT) for diagnostic evaluation has increased dramatically over the past 2 decades. Even though CT is associated with substantially higher radiation exposure than conventional radiography, typical doses are not known. We sought to estimate the radiation dose associated with common CT studies in clinical practice and quantify the potential cancer risk associated with these examinations.

Methods: We conducted a retrospective cross-sectional study describing radiation dose associated with the 11 most common types of diagnostic CT studies performed on 1119 consecutive adult patients at 4 San Francisco Bay Area institutions in California between January 1 and May 30, 2008. We estimated lifetime attributable risks of cancer by study type from these measured doses.

Results: Radiation doses varied significantly between the different types of CT studies. The overall median effective doses ranged from 2 millisieverts (mSv) for a routine head CT scan to 31 mSv for a multiphase abdomen and pelvis CT scan. Within each type of CT study, effective dose varied significantly within and across institutions, with a mean 13-fold variation between the highest and lowest dose for each study type. The estimated number of CT scans that will lead to the development of a cancer varied widely depending on the specific type of CT examination and the patient's age and sex. An estimated 1 in 270 women who underwent CT coronary angiography at age 40 years will develop cancer from that CT scan (1 in 600 men), compared with an estimated 1 in 8100 women who had a routine head CT scan at the same age (1 in 11 080 men). For 20-year-old patients, the risks were approximately doubled, and for 60-year-old patients, they were approximately 50% lower.

Conclusion: Radiation doses from commonly performed diagnostic CT examinations are higher and more variable than generally quoted, highlighting the need for greater standardization across institutions.

Arch Intern Med. 2009;169(22):2078-2086

COMPUTED TOMOGRAPHY (CT) use has increased dramatically over the past several decades.[1] The total number of CT examinations performed annually in the United States has risen from approximately 3 million in 1980 to nearly 70 million in 2007.[2,3] Integrating CT into routine care has improved patient health care dramatically, and CT is widely considered among the most important advances in medicine. However, CT delivers much higher radiation doses than do conventional diagnostic x-rays. For example, a chest CT scan typically delivers more than 100 times the radiation dose of a routine frontal and lateral chest radiograph.[4,5] Furthermore, radiation exposure from CT examinations has also increased, in part due to the increased speed of image acquisition allowing vascular, cardiac, and multiphase examinations, all associated with higher doses. Thus, greater use of CT has resulted in a concurrent increase in the medical exposure to ionizing radiation.[2,6]

See also page 2049 and 2071

Exposure to ionizing radiation is of concern because evidence has linked exposure to low-level ionizing radiation at doses used in medical imaging to the development of cancer. The National Academy of Sciences' National Research Council comprehensively reviewed biological and epidemiological data related to health risks from exposure to ionizing radiation, recently published as the Biological Effects of Ionizing Radiation (BEIR) VII Phase 2 report.[7] The epidemiologic data described atomic bomb survivors, populations who lived near nuclear facilities during accidental releases of radioactive materials such as Chernobyl, workers with occupational exposures, and populations who received exposures from diag-

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Table 1. Types of Computed Tomographic (CT) Examinations Included in Our Report and the Typical Clinical Indications That Led to These Examinations[a]

Anatomic Area, Protocol	Clinical Indications
Head and neck	
Routine head	Focal neurologic signs or symptoms suggestive of hydrocephalus, hemorrhage or neoplasia; trauma
Routine neck	Pain; trauma; mass; suspected abscess
Suspected stroke	Focal neurological signs or symptoms suggestive of stroke; acute headache with risk factors for aneurysm
Chest	
Routine chest, no contrast	Pain; trauma; hypoxia
Routine chest, with contrast	Pain; trauma; hypoxia; suspected neoplasia
Suspected pulmonary embolism	Pain; tachycardia; shortness of breath; hypoxia; suspected pulmonary embolism
Coronary angiogram	Ischemia, suspected stenosis; assess bypass grafts, coronary artery anomalies; acute chest pain
Abdomen and pelvis	
Routine abdomen-pelvis, no contrast	Pain; trauma
Routine abdomen-pelvis, with contrast	Pain; trauma; suspected neoplasia; fever of unknown origin; suspected abscess, appendicitis or diverticulitis
Multiphase abdomen-pelvis	Suspected liver, pancreas, or renal neoplasia; suspected hepatitis or pancreatitis; suspected renal stone
Suspected aneurysm or dissection	Acute or radiating chest or back pain; trauma; vasculitis

[a]The 3 types of studies in the head and neck comprised 25.7% of all CTs; the 4 types of studies in the chest comprised 24.7% of all CTs; and the 4 types of studies in the abdomen and pelvis comprised 29.5% of all CTs.

nostic and therapeutic medical studies. Radiation doses associated with commonly used CT examinations resemble doses received by individuals in whom an increased risk of cancer was documented. For example, an increased risk of cancer has been identified among long-term survivors of the Hiroshima and Nagasaki atomic bombs, who received exposures of 10 to 100 millisieverts (mSv).[8-11] A single CT scan can deliver an equivalent radiation exposure,[12] and patients may receive multiple CT scans over time.[13]

Even though the risk to an individual patient may be small, the increasingly large number of people exposed, coupled with the increasingly high exposure per examination, could translate into many cases of cancer resulting directly from the radiation exposure from CT. It is important to understand how much radiation medical imaging delivers, so this potential for harm can be balanced against the potential for benefit. This is particularly important because the threshold for using CT has declined, and CT is increasingly being used among healthy individuals, in whom the risk of potential carcinogenesis from CT could outweigh its diagnostic value. To date, relatively few data describe how much radiation is received through the most common types of CT examinations when applied in clinical practice, as most published studies focused on phantom studies. Computed tomographic coronary angiography is the only examination that has been studied in detail. Our study aimed to estimate how much radiation exposure is associated with the types of CT examinations performed most commonly in the United States; to estimate variation across study types, patients, and institutions; and to use these data to estimate the lifetime attributable risk (LAR) of cancer associated with these tests.

METHODS

Data were collected at 4 institutions in the San Francisco Bay Area in California: the University of California, San Francisco (UCSF), a 600-bed academic medical center in San Francisco; Alta Bates Summit Medical Center, a 555-bed private, community-based medical center in Berkeley; Marin General Hospital, a 235-bed acute care hospital serving Marin County; and California Pacific Medical Center, a private, community-based hospital with 1300 beds in San Francisco. These facilities were selected because of their relatively large size, diverse San Francisco Bay Area locations that allow for geographic diversity, availability of picture archiving and communications systems (PACS) that let us select particular types of CT examinations on consecutive patients at each institution, and reporting systems that allowed us to query the clinical reasons studies were ordered. Furthermore, each institution used the same manufacturer's CT scanners, letting us collect dose information consistently across sites. The institutional review boards at each participating institution approved the study.

SELECTION OF SPECIFIC CT STUDY TYPES

We abstracted radiation dose information on the most commonly performed types of diagnostic CT examinations. To determine the most frequent CT study types, we queried the UCSF Radiology Information System for all CT examinations performed in a single month (March 2008) and defined common study types as the 11 composing at least 1% of the total number of CT examinations (**Table 1**). We excluded examinations performed in association with a therapeutic procedure, such as CT-guided abscess drainage.

SELECTION OF PATIENT STUDIES

We sampled 20 to 30 consecutive patients 18 years and older from each of the 4 institutions for each of the study types between January 1, 2008, and May 31, 2008, for a total sample of 1119 patients. Our assessment of the dose associated with CT coronary angiography is limited to 2 institutions that routinely saved radiation dose data from this study type. For each patient, the technical parameters and dose report data (scan area, scan length, slice thickness, kVp [kilovolts (peak)], mAs [milliamperes per second], pitch, and dose-length product [DLP]) were abstracted from the CT images.

RADIATION DOSE

It is impractical to directly measure the radiation dose absorbed by individual patients even when the radiation emitted

by a machine is precisely known. Instead, radiation exposure may be quantified using various methods. We used "effective dose" to quantify the radiation exposure associated with each CT examination because this is one of the most frequently reported measurements.[14] Furthermore, effective dose allows comparison across the different types of CT studies and between CT and other imaging tests, facilitating comparison of CT to the most common radiology studies patients undergo. The effective dose accounts for the amount of radiation to the exposed organs and each organ's sensitivity to developing cancer from radiation exposure. An explanation and glossary is included in the eAppendix (first section) (http://www.archinternmed.com). We estimated the effective dose using the DLP, which is recorded as part of the CT scan. The DLP is an approximation of the total energy a patient absorbs from the scan. We combined the DLP with details of the area imaged and used conversion factors to translate this into an effective dose that takes into account the sensitivities of different organs to developing radiation-induced cancer.[15,16] A comparison of our approach to a more detailed approach based on organ-specific dose estimates using a computer software program (ImPACT CT Patient Dosimetry Calculator version 0.99x)[17] is included in the eAppendix (second section).

STATISTICAL ANALYSIS

Descriptive statistics of the effective doses were calculated for each CT study type, and differences within and across institutions were assessed using analysis of variance (ANOVA). Because the distributions of doses were right skewed, we modeled the log transformation of dose to better satisfy ANOVA's assumption of normally distributed outcomes. To calculate the variation in dose, for each CT study type, we calculated the difference between the highest and lowest dose observed. To put the dose estimates in the context that patients and physicians can readily understand, the effective dose for each CT study type was compared with the effective doses for the 2 most common conventional radiology studies in the United States—a frontal and lateral chest radiography series (effective dose of 0.065 mSv)[18] and a screening mammography series (including 2 views of each breast, effective dose of 0.42 mSv)[18]—using the ImPACT CT Patient Dosimetry Calculator version 0.99x[17] among a random subset of 18 patients.

Although effective dose best reflects a patient's overall exposure to radiation, organ-specific dose may be more appropriate for estimating lifetime cancer risk for nonuniform exposures such as CT. For example, if a patient undergoes an imaging study that radiates only the breast, her risk of cancer from that examination will primarily reflect her increased risk of breast cancer. As an example of how organ-specific dose varies between CT and conventional radiography, we show for CT coronary angiography, which primarily imparts radiation to the lungs and to the breasts, a comparison between its organ-specific absorbed doses with those of a chest series (lung dose, 0.06 mGy) (to convert to millirads, multiply by 100) and a mammography series (breast dose, 3.5 mGy).[18]

ESTIMATING LAR OF CANCER

The BEIR VII (2006) report provides a method to estimate LAR of cancer based on the magnitude of a single radiation exposure and a patient's age at the time of that exposure.[7] The LAR is defined as additional cancer risk above and beyond baseline cancer risk. This can be calculated for specific cancers as well as for all cancers combined. The age- and sex-specific LAR of all cancer incidence for the median and interquartile range of effective doses, for each type of study, was calculated using the BEIR VII risk estimates. We used all cancer as the outcome to compare all types of CT studies included in this report. For comparison purposes, we also estimated the LAR of cancer using a second approach for a subset of patients for whom we have more detailed dose information (see eAppendix [third section] and eFigure), and we used these results to develop an adjustment. We estimated the number of patients undergoing CT that would lead to the development of 1 radiation-induced cancer, by type of CT examination, age at the time of exposure, and sex. For each type of study, we also ranked the patients from those who received the lowest to highest effective dose and calculated the adjusted LAR of cancer corresponding to each effective dose, had those doses been received by patients aged 20, 40, or 60 years.

RESULTS

Table 1 gives the types of CT studies we examined and the clinical indications that led to them. Across all study types, the mean patient age was 59 years and 535 of the 1119 patients (48%) were female. These 11 study types comprise approximately 80% of all CTs performed. The remaining types of CT studies not included reflect a large number of additional study types, none of which contributed more than 1% to the total number of CTs.

VARIATION IN DOSE BETWEEN STUDY TYPES

Within each anatomic area, the median effective dose varied widely between study types (**Table 2**). For scans of the head and neck, the median effective dose varied from 2 mSv for a routine head (interquartile range [IQR], 2-3 mSv) to 14 mSv (IQR, 9-20 mSv) for a suspected stroke CT. For chest scans, the median effective dose varied from 8 mSv (IQR, 5-11 mSv) for a routine chest to 22 mSv (IQR, 14-24 mSv) for coronary angiography. For abdomen and pelvis scans, a routine CT scan without contrast had the lowest median effective dose (15 mSv [IQR, 10-20 mSv]), whereas a multiphase abdominal and pelvis CT scan had the highest median effective dose (31 mSv [IQR, 21-43 mSv]). For each anatomic area, studies that included an assessment of arteries (ie, suspected stroke, coronary angiography, suspected aneurysm or dissection) and the multiphase studies had higher exposures, resulting from the use of repeated series with these study types. Table 2 also gives the comparable number of conventional projection radiographs that result in a similar effective dose. The median effective dose delivered through a single CT scan was as high as 74 mammography series and 442 chest radiography series. Our comparison of organ-specific doses demonstrated that a CT coronary angiogram delivers a dose to the breast that is equivalent to approximately 15 mammography studies (51 mGy breast dose for CT coronary angiogram vs 3.5 mGy breast dose for a mammography series) and delivers a dose to the lung that is equivalent to 711 chest radiography series (64 mGy lung dose for CT coronary angiogram vs 0.09 mGy lung dose for a frontal and lateral chest radiograph).

VARIATION IN DOSE WITHIN STUDY TYPES

Even within study type, radiation dose varied substantially (**Figure 1**). There was a mean 13-fold variation

Table 2. Median Effective Radiation Dose (IQR, Minimum and Maximum) for Each Type of CT Study

Anatomic Area, Type of CT Study	No.	CT Effective Dose, mSv		Conventional Radiographs Resulting in Equivalent Dose	
		Median (IQR)	Absolute Range, Min-Max	Chest Radiography Series	Mammography Series
Head and neck					
Routine head	120	2 (2-3)	0.3-6	30	5
Routine neck	115	4 (3-6)	0.7-9	55	9
Suspected stroke	87	14 (9-20)	4-56	199	33
Chest					
Routine chest, no contrast	120	8 (5-11)	2-24	117	20
Routine chest, with contrast	120	8 (5-12)	2-19	119	20
Suspected pulmonary embolism	120	10 (7-14)	2-30	137	23
Coronary angiogram	34	22 (14-24)	7-39	309	51
Abdomen-pelvis					
Routine abdomen-pelvis, no contrast	120	15 (10-20)	3-43	220	37
Routine abdomen-pelvis, with contrast	117	16 (11-20)	4-45	234	39
Multiphase abdomen-pelvis	110	31 (21-43)	6-90	442	74
Suspected aneurysm or dissection	56	24 (20-37)	4-68	347	58

Abbreviations: IQR, interquartile range; mSv, millisievert.

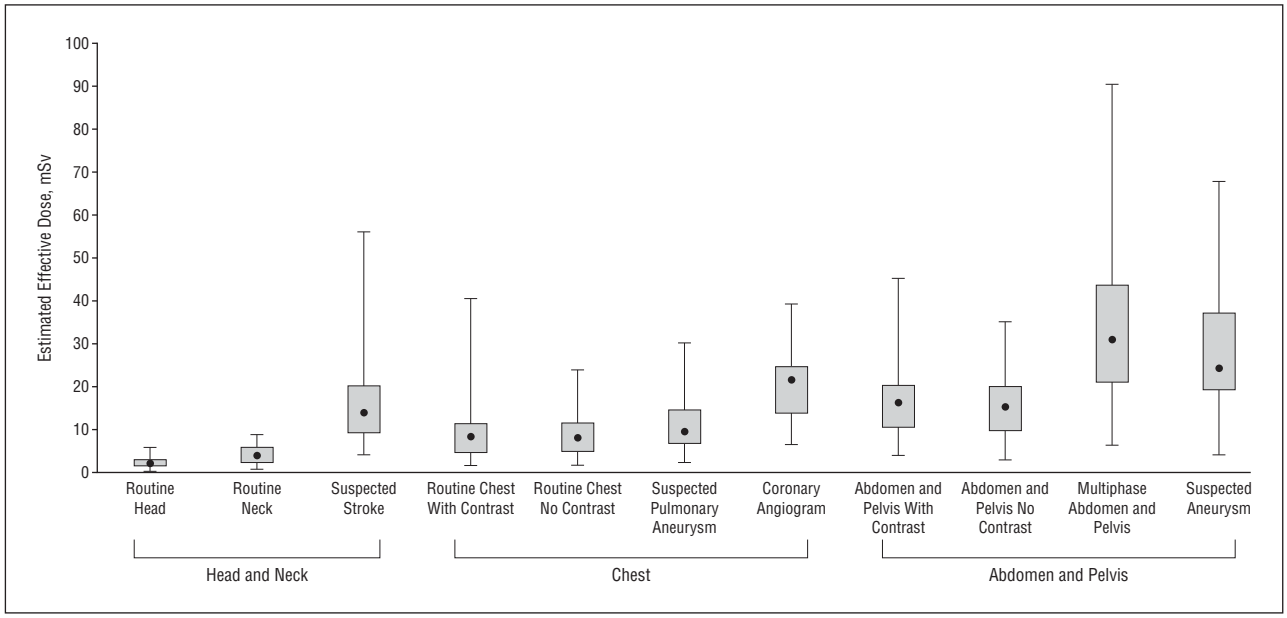

Figure 1. Distribution of median (interquartile range) estimated effective dose by computed tomography study type. The "whiskers" show the minimum and maximum observed values. mSv indicates milli-sievert.

between the highest and lowest dose for each CT study type included (range, 6- to 22-fold difference across the different study types). The effective doses tended to be higher and more variable in the abdomen and pelvis, where the widest range in dose was documented for multiphase abdomen and pelvis CT scanning (range, 6-90 mSv). The variation in doses occurred both within and across institutions (**Table 3**). The mean doses differed 2-fold across institutions, and for several of the study types, the mean dose across institutions differed by 3-fold or more. For example, the mean (SD) effective dose for a suspected stroke CT was 8 (2) mSv at site 3 compared with 29 (8) mSv at site 4. We observed no consistent pattern for which institution had the highest radiation dose; rather, each site had the highest dose for at least one of the included study types.

ADJUSTED LARs OF CANCER

For 6 of the study types, the estimated effective doses for each study type, sorted from the lowest (1%) to the highest (100%) across patients, and the corresponding adjusted LAR of cancer are shown in **Figure 2**, assuming all examinations were received by a 20-year-old woman. For a routine head CT scan, the median effective dose was 2 mSv, and the corresponding median adjusted LAR of cancer was 0.23 cancers per 1000 patients (range, 0.03-0.70 cancers per 1000 patients).

Table 3. Mean (SD) Effective Dose for Each Type of CT Study at Each of the 4 Sites

Anatomic Area, Type of CT Study	Effective Dose, Mean (SD), mSv				*P* Value
	Site 1 (n=295)	Site 2 (n=282)	Site 3 (n=280)	Site 4 (n=262)	
Head and neck					
Routine head	3 (1)	2 (0.3)	3 (1)	2 (0.4)	<.001
Routine neck	3 (1)	6 (2)	5 (1)	2 (0.6)	<.001
Suspected stroke	18 (13)	15 (3)	8 (2)	29 (8)	<.001
Chest					
Routine chest, no contrast	5 (3)	12 (7)	11 (4)	7 (3)	<.001
Routine chest, with contrast	7 (5)	11 (5)	11 (4)	8 (4)	<.001
Suspected pulmonary embolism	8 (3)	21 (7)	9 (2)	9 (3)	<.001
Coronary angiogram	21 (9)	19.7 (6)			=.75
Abdomen and pelvis					
Routine abdomen-pelvis, no contrast	12 (7)	19 (7)	20 (7)	12 (5)	<.001
Routine abdomen-pelvis, with contrast	12 (6)	16 (7)	20 (7)	15 (6)	<.001
Multiphase abdomen-pelvis	24 (13)	35 (8)	45 (14)	34 (17)	<.001
Suspected aneurysm or dissection	49 (14)	25 (18)	22 (8)	25 (10)	<.001

Abbreviations: CT, computed tomography; mSv, millisievert.

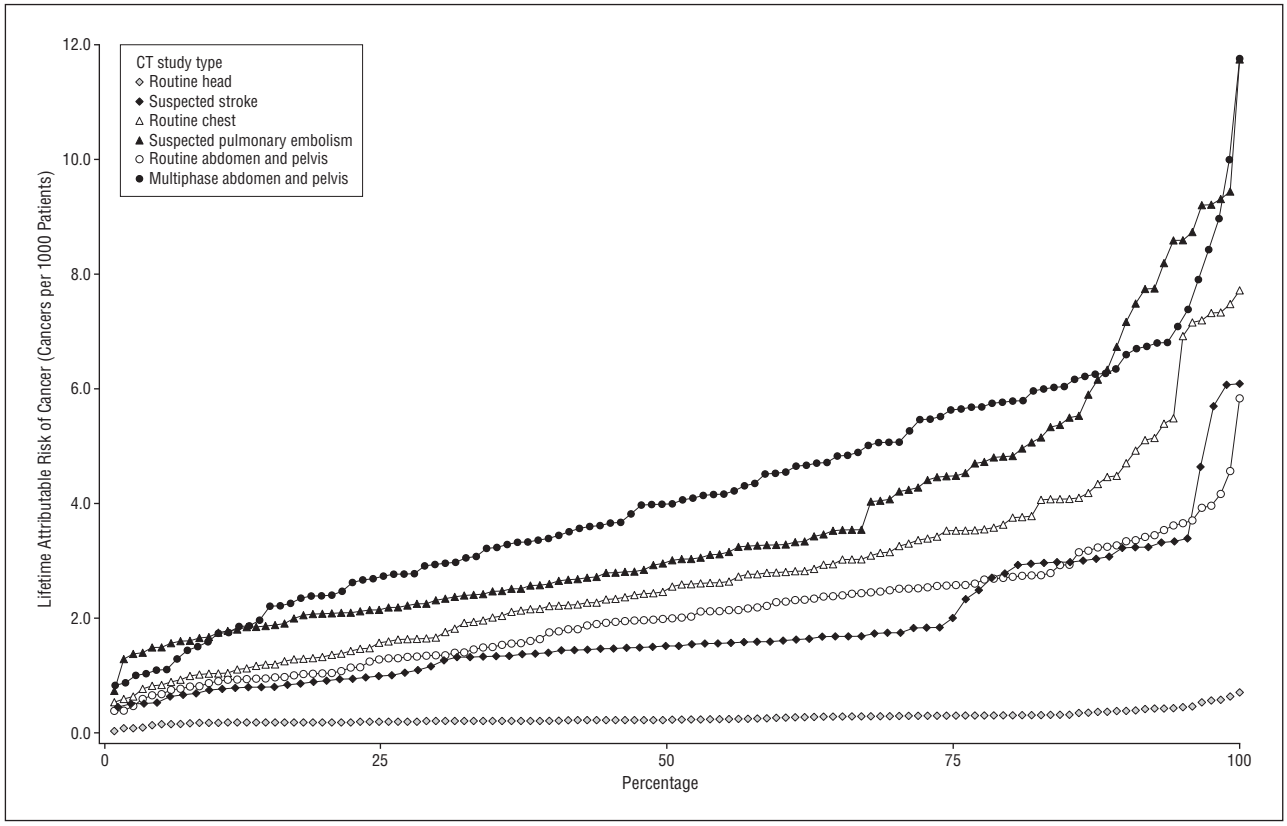

Figure 2. Estimated range in the lifetime attributable risk of cancer if a 20-year-old woman underwent one of several types of computed tomographic (CT) studies using the distribution in radiation dose exposure from our report. The x-axis represents the estimated effective doses for each study type, sorted from the lowest (1%) to the highest (100%) across patients.

For a multiphase abdomen and pelvis CT scan, the median effective dose was 31 mSv, and the corresponding median adjusted LAR of cancer was 4 cancers per 1000 patients (range, 0.8-11.1 cancers per 1000 patients). For some study types, the range in the associated effective dose was narrow, with a correspondingly narrow range in the adjusted LARs of cancer (eg, routine head CT). In contrast, the effective dose for most studies had a much wider range with a correspondingly broad range in the adjusted LARs of cancer.

THE ESTIMATED NUMBER OF CTs THAT WOULD LEAD TO CANCER BY STUDY TYPE

For each study type, **Table 4** gives the estimated number of patients undergoing CT that would lead to the de-

Table 4. Estimated Number of Patients Undergoing Computed Tomography (CT) That Would Lead to the Development of 1 Radiation-Induced Cancer, by Type of CT Examination and Age at the Time of Exposure, Based on the Median and Interquartile Radiation Dose Observed

Anatomic Area, Type of CT Study	Patients, Median (Interquartile Range), No.					
	Age, 20 y		Age, 40 y		Age, 60 y	
	Female	Male	Female	Male	Female	Male
Head and neck						
Routine head	4360 (3290-5110)	7350 (5540-8620)	8100 (6110-9500)	11 080 (8350-12 990)	12 250 (9230-14 360)	14 680 (11 070-14 680)
Routine neck	2390 (1640-3540)	4020 (2770-5970)	4430 (3050-6580)	6058 (4170-8990)	6700 (4620-9940)	8030 (5530-8030)
Suspected stroke	660 (460-980)	1120 (770-1650)	1230 (850-1820)	1682 (1170-2490)	1860 (1290-2750)	2230 (1550-2230)
Chest						
Routine chest, no contrast	390 (290-630)	1040 (770-1670)	720 (540-1160)	1566 (1170-2520)	1090 (820-1760)	2080 (1550-2080)
Routine chest, with contrast	380 (270-650)	1020 (710-1740)	720 (500-1210)	1538 (1070-2620)	1070 (750-1830)	2040 (1420-2040)
Suspected pulmonary embolism	330 (230-460)	880 (610-1220)	620 (420-850)	1333 (920-1840)	930 (640-1280)	1770 (1220-1770)
Coronary angiogram	150 (130-230)	390 (350-610)	270 (250-420)	595 (540-920)	420 (370-640)	790 (710-790)
Abdomen and pelvis						
Routine abdomen-pelvis, no contrast	500 (380-770)	660 (510-1024)	930 (710-1430)	1002 (770-1540)	1400 (1080-2160)	1330 (1020-1330)
Routine abdomen-pelvis, with contrast	470 (380-700)	620 (510-930)	870 (710-1300)	942 (770-1400)	1320 (1080-1960)	1250 (1020-1250)
Multiphase abdomen-pelvis	250 (180-370)	330 (240-490)	460 (330-680)	498 (360-730)	700 (500-1030)	660 (480-660)
Suspected aneurysm or dissection	320 (210-390)	420 (280-510)	590 (390-710)	636 (420-770)	890 (580-1080)	840 (550-840)

velopment of 1 radiation-induced cancer, by age at exposure and sex. As expected, the number of CT scans that would result in a cancer varies widely by sex, age, and study type. Reflecting a higher cancer risk of radiation among women, it would take far fewer CT scans to result in a cancer among women compared with men. Coronary angiography had the lowest number of CT scans that would result in a single cancer. Among 40-year-old women who underwent coronary angiography CT, we estimate that 1 cancer would be expected to occur among approximately 270 women as a result of the radiation exposure of the examination (IQR, 1 in 250 to 1 in 420). In contrast, it would take the largest numbers of routine head CT scans to result in a single cancer. Among 40-year-old women, 1 cancer would occur among 8105 patients who underwent a routine head CT scan (IQR, 1 in 6110 to 1 in 9500). For a 60-year-old woman, the risks were substantially lower and varied from approximately 1 in 420 examinations for CT coronary angiography (IQR, 1 in 370 to 1 in 640) to 1 in 12 250 examinations for a routine head CT scan (IQR, 1 in 9230 to 1 in 14 360). For a 20-year-old woman, the risks were substantially higher and varied from approximately 1 in 150 examinations for CT coronary angiography (IQR, 1 in 130 to 1 in 230) to 1 in 4360 examinations for a routine head CT scan (IQR, 1 in 3290 to 1 in 5110).

COMMENT

We documented higher and more variable doses than what is typically quoted from the most common types of diagnostic CT studies performed in clinical practice. For example, the median effective dose of an abdomen and pelvis CT scan (the most common type of CT examination performed in the United States[12]) is often quoted as 8 to 10 mSv.[6,16,19] Yet we found that the median dose of a routine abdomen and pelvis CT scan was 66% higher, and the median dose of a multiphase abdomen and pelvis CT scan was nearly 4-fold higher. Furthermore, we found substantial variation in doses within and across institutions, with a mean 13-fold variation between the highest and lowest dose for each CT study type included. Thus, depending on where an individual patient received imaging and the specific technical parameters used, the effective dose received could substantially exceed the median. While some of this variation may be clinically indicated to accommodate patients of different size or the specifics of the clinical question that was being addressed, the variation in effective dose was dramatic and of greater magnitude than widely considered acceptable, particularly considering that the patients were already stratified within relatively well-defined clinical groups. The variation in dose across the 4 clinical sites reflects site-specific methods of choosing different technical parameters to answer the same clinical question.

The corresponding LARs of cancer were also higher than typically reported and markedly variable by study type, patient, and hospital. For example, it is commonly reported that a CT scan may be associated with an increase in the risk of cancer of approximately 1 in 2000.[2,19] Based on the highest effective dose we observed, a 20-year-old women who underwent a CT for suspected pulmonary embolism, a CT coronary angiography or a multiphase abdomen and pelvis CT scan could have an associated increased risk of developing cancer of as high as 1 in 80 (Figure 2). The risks declined substantially with age and were lower for men, so radiation-associated cancer risks are of particular concern for younger, female patients. It is precisely because the risks of cancer are so high among younger patients that we chose to illustrate the risk of cancer when CT is used in a 20-year-old female patient. Although it is generally assumed that very little CT imaging occurs in children and young adults, approximately 5% of all CT examinations are performed in children, 10% of all CT examinations are performed in those aged 20 to 30 years, and 5% of 20-year-old patients undergo CT imaging per year.[20] Also, the fre-

quency of CT imaging in children and young adults is increasing.

The doses we documented may be higher than typically reported for 3 main reasons. First, we estimated radiation doses received by patients in clinical practice, whereas many previous studies have assessed the dose received in idealized settings on phantoms, ie, sophisticated plastic models created to measure dose when put in a real scanners. Study parameters applied in phantoms may differ substantially from those used in actual clinical settings.[21,22]

Second, most prior work described experience at a single institution or a single type of CT study, where the specific instructions for conducting studies may be standardized. We studied patients in clinical practice, who underwent imaging for a range of symptoms and clinical indications, and across different institutions, where there was no standardization related to our study. For example, a common clinical indication for a multiphase abdomen and pelvis CT scan is suspected renal cancer in patients with hematuria (blood in the urine). This type of study may start out as a single phase, noncontrast examination (a low-dose study to assess for renal calculi) but may be expanded to include contrast and multiple phases of imaging to evaluate for renal or bladder cancer (a resulting high-dose study). In fact, the variation in the evaluation of this symptom was dramatic, with large differences in the number of series that were obtained, both within and across institutions, contributing to the large difference in means and standard deviations for this study type.

Third, most prior work grouped all studies within the same anatomic area together; however, even within one anatomic area, not all CT scans involve similar doses. Protocols requiring more images by increasing the scan length or repeatedly scanning through the same area result in higher radiation exposure. For example, an increasingly common indication for CT is to assess a patient for the possibility of pulmonary embolism. The mean effective doses for 3 of the hospitals for the suspected pulmonary embolism CT were 8, 9, and 9 mSv, whereas the mean effective dose for the fourth site was 21 mSv. The fourth was the only site where, in addition to images through the chest to directly assess for pulmonary embolism, they also increased the scan length and scanned through the patient's pelvis and proximal thighs to assess for the presence of deep vein thromboses. While it is not uncommon, nor necessarily unreasonable, to include lower-extremity venography when a patient is referred for suspected pulmonary embolism CT (pulmonary embolisms and deep vein thromboses are considered 2 manifestations of 1 pathologic process and share the same treatment[23]), this difference in CT protocol leads to a substantial increase in radiation exposure and thus cancer risk. We found radiation exposure was more than 2-fold greater for this study type when the extra images were included. A 2-fold difference in average radiation exposure is not insignificant and needs to be considered when specific protocols are set and needs to be understood by referring clinicians when they weigh the risks and benefits of this study.

The possibility that CT may cause more cancers than it prevents has been raised with respect to full-body screening CT examinations conducted in asymptomatic persons.[24] In contrast, CT is generally considered to have a very favorable risk to benefit profile among symptomatic patients. However, the threshold for using CT has declined so that it is no longer used only in very sick patients but also in those with mild, self-limited illness who are otherwise healthy. In these patients, the value of CT needs to be balanced against this small but real risk of carcinogenesis resulting from its use. Neither physicians[25,26] nor patients[27] are generally aware of the radiation associated with CT, its risk of carcinogenesis, or the importance of limiting exposure among younger patients. It is important to make both physicians and patients aware that this risk exists.

Consensus is growing that patients' exposure to radiation through medical imaging needs to be reduced, and we believe that 3 general approaches should be taken. First, CT examination protocols and techniques should be optimized and standardized to limit the radiation associated with individual scans. This would include standardizing protocols across sites, reducing multiple series within each examination, implementing dose reduction strategies, and encouraging participation in accreditation programs such as that offered by the American College of Radiology. In practice, these guidelines have not been widely embraced, perhaps because no regulatory component is associated with their use. While the Food and Drug Administration (FDA) requires manufacturers to record dosing information when phantoms are scanned using set imaging parameters, the FDA does not monitor or regulate the dose associated with clinical CT applications. In contrast, the FDA monitors and regulates the dose associated with mammography examinations and has successfully standardized the associated doses. Creating specific standards for CT examinations and requiring adoption would lead to a reduction in mean and outlier doses. For example, for some CT study types, dose reduction techniques can reduce the dose by 50% or greater.[28] Great Britain and several European countries have been more aggressive in trying to limit radiation exposure from CT with some success.[29] Interestingly, a recent report of the doses associated with CT coronary angiography documented substantial variation in dose across facilities, but the mean effective dose they report was approximately half the effective dose we found for the same type of CT study.[30] Many of the study sites were in the United Kingdom and Europe, where efforts to minimize radiation dose have been ongoing for several years. Among pediatric patients, efforts have been more common and successful to reduce the radiation dose,[31] in part resulting from articles highlighting that when standard adult settings are used in children, the resulting cancer risks are much higher.[32]

A second approach to minimize medical radiation exposure should focus on reducing the number of CT examinations. Although difficult to fully assess, it has been reported that 30% or more of the CT examinations currently performed may be unnecessary. The European Commission Office of Radiation Protection and the Canadian Association of Radiologists developed guidelines highlighting where CT imaging should be curtailed,[33,34] including repeating investigations that have

already been done; imaging when it is unlikely to affect patient management because a positive finding is irrelevant, such as assessment and surveillance of incidental findings; investigating too often—before the disease could have progressed or before the results could influence treatment; performing the wrong investigation; and overinvestigating. Many CT examinations in the United States fall into these categories, for example, the repeated use of CT for patients with documented renal stones, and more explicit discussion and guidelines are needed on how to reduce these unnecessary CT studies.

The third approach to reducing exposure may be to track and collect dose information at the patient level because patients may undergo repeated imaging over time.[13] Tracking detailed dose information at the patient level and in a systemwide fashion such as within a searchable, electronic medical record would help educate patients and health care providers about radiation exposure and could facilitate activities to minimize dose when possible. The impact of this could be particularly dramatic among the subset of patients who have repeated imaging and who are thus at greatest risk of radiation-associated cancer.

Our study has several strengths. We collected data from 4 large institutions, which included an average of 100 patients for each type of study, and results were collected on consecutive patients for each study type at each institution. We also included the most frequent types of CT examinations patients undergo, making the results highly relevant. Furthermore, we collected data from actual clinical practice.

Our study also has several weaknesses. Our cohort was insufficiently large to understand the reasons for variation of dose associated with each type of study, including the technologist's experience, the availability of physicians to check studies in real time that might lead them to add or subtract additional series, geographic variation, type and specific dose-reduction or dose-modulation algorithms available or used, and patient level factors (such as weight) that may have led to differences in dose. Our work highlights the pressing need for large national studies to understand how these factors contribute to variation in dose. Similarly, we did not assess the relationship between image quality and radiation dose; there is a pressing need to determine optimum dose for each type of study that balances image quality with keeping the doses as low as possible. We grouped studies by the clinical indications that led to the studies, but there may have been imprecision in our characterizing the indications that led to these studies. All scans were performed using a single manufacturer's scanners, but doses depend on manufacturer and model. Limiting the results to a single manufacturer will have underestimated the true variation in dose. The methods we used to assess radiation dose are imprecise. We presented "effective dose," calculated using the scanner-provided DLP measurement, because this is simple to calculate, straightforward, and reliable and thus can be used as an easy starting point to begin to record patient-level exposure. Although different metrics will yield slightly different estimates[35] and these methods are based on assumptions of patient size that may not be applicable to all patients, this method is highly concordant with other methods of estimating dose.[36,37] Similarly, we used a simple method to estimate LAR but found high agreement with a more detailed method that relies on organ doses calculated with computer simulation models. However, this method needs to be further validated and refined among a larger group of patients. Furthermore, several other uncertainties exist in the methods used to project lifetime risk from radiation exposure,[7] so the LARs should not be viewed as exact patient risks. Lastly, the LAR of cancer needs to be put into context of the patients' remaining life expectancy, and our calculations were based on the assumption of normal life expectancy. For individuals with lower life expectancy, these estimates will overestimate their lifetime risk; if mortality rates were increased by 20%, the risks of carcinogenesis would have been overestimated by 5%.[38]

The radiation exposure associated with CT has increased substantially over the past 2 decades, and efforts need to be undertaken to minimize radiation exposure from CT, including reducing unnecessary studies, reducing the dose per study, and reducing the variation in dose across patients and facilities. Patient outcomes studies are needed to help define when CT leads to the greatest benefit and when these studies may have no impact, where that the radiation risk may be greater than the benefit expected from the examinations. Understanding exposures to medical radiation delivered through actual clinical studies is a crucial first step toward developing reasonable strategies to minimize unnecessary exposures.

Accepted for Publication: September 14, 2009.
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Financial Disclosure: None reported.

Funding/Support: This study was funded by the National Institutes of Health (NIH) National Institute of Biomedical Imaging and BioEngineering training grant T32 EB001631, NIH National Cancer Institute grants CA125036 and CA 131698, and the UCSF School of Medicine Bridge Funding Program.

Role of the Sponsor: None of the funders were involved in the design and conduct of the study; collection, management, analysis, and interpretation of the data; or preparation, review, or approval of the manuscript.

Online-Only Material: The eAppendix and eFigure are available at http://www.archinternmed.com.

Additional Contributions: Edward Baker, MD (California Pacific Medical Center, San Francisco), Dennis Orwig, MD (Marin General Hospital, Greenbrae, California), Erik Gaensler, MD (Alta Bates Medical Center, Berkeley, California), and John Boone, PhD (University of California, Davis), provided generous help in completing this work.

REFERENCES

1. Medicare Payment Advisory Commission. *A Data Book: Healthcare Spending and the Medicare Program.* June 2007. http://www.medpac.gov/documents/Jun08DataBook_Entire_report.pdf. Accessed November 15, 2008.
2. Amis ES Jr, Butler PF, Applegate KE, et al; American College of Radiology. American College of Radiology white paper on radiation dose in medicine. *J Am Coll Radiol.* 2007;4(5):272-284.
3. IMV Medical Information Division. *CT Census Database and Market Summary Report.* Greenbelt, MD: IMV; 2008.
4. Linet MS, Kim KP, Rajaraman P. Children's exposure to diagnostic medical radiation and cancer risk: epidemiologic and dosimetric considerations. *Pediatr Radiol.* 2009;39(S1)(suppl 1):S4-S26.
5. Mettler FA Jr, Huda W, Yoshizumi TT, Mahesh M. Effective doses in radiology and diagnostic nuclear medicine: a catalog. *Radiology.* 2008;248(1):254-263.
6. National Council on Radiation Protection and Measurements. *Ionizing Radiation Exposure of the Population of the United States.* 2009. NCRP report 160. http://www.ncrponline.org/. Accessed October 7, 2009.
7. Board of Radiation Effects Research Division on Earth and Life Sciences National Research Council of the National Academies. *Health Risks From Exposure to Low Levels of Ionizing Radiation: BEIR VII Phase 2.* Washington, DC: National Academies Press; 2006.
8. Pierce DA, Preston DL. Radiation-related cancer risks at low doses among atomic bomb survivors. *Radiat Res.* 2000;154(2):178-186.
9. Preston DL, Ron E, Tokuoka S, et al. Solid cancer incidence in atomic bomb survivors: 1958-1998. *Radiat Res.* 2007;168(1):1-64.
10. Preston DL, Pierce DA, Shimizu Y, Ron E, Mabuchi K. Dose response and temporal patterns of radiation-associated solid cancer risks. *Health Phys.* 2003;85(1):43-46.
11. 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 U S A.* 2003;100(24):13761-13766.
12. Mettler FA Jr, Thomadsen BR, Bhargavan M, et al. Medical radiation exposure in the US in 2006: preliminary results. *Health Phys.* 2008;95(5):502-507.
13. Sodickson A, Baeyens PF, Andriole KP, et al. Recurrent CT, cumulative radiation exposure, and associated radiation-induced cancer risks from CT of adults. *Radiology.* 2009;251(1):175-184.
14. International Commission on Radiological Protection. *Managing Patient Dose in Multi-Detector Computed Tomography (MDCT).* Ottawa, Ontario, Canada: International Commission on Radiological Protection; 2007.
15. Shrimpton PC, Hillier MC, Lewis MA, Dunn M. National survey of doses from CT in the UK: 2003 [published correction appears in *Br J Radiol.* 2007 Aug;80(956):685]. *Br J Radiol.* 2006;79(948):968-980.
16. American Association of Physicists in Medicine. *The Measurement, Reporting and Management of Radiation Dose in CT: Report of AAPM Task Group 23 of the Diagnostic Imaging Council CT Committee.* College Park, MD: American Association of Physicists in Medicine; 2008. AAPM report 96.
17. ImPACT Group Web site. http://www.impactscan.org/. Accessed October 7, 2009.
18. National Cancer Institute. Radiation risks and pediatric computed tomography (CT): a guide for health care providers. 2009. http://www.cancer.gov/cancertopics/causes/radiation-risks-pediatric-CT. Accessed October 7, 2009.
19. US Food and Drug Administration. What are the radiation risks from CT? 2008. http://www.fda.gov/cdrh/CT/risks.html. Accessed October 7, 2009.
20. Smith-Bindman R, Miglioretti D, Larson E. Rising use of diagnostic medical imaging in an large integrated health plan. *Health Aff (Millwood).* 2008;26(6):1491-1502.
21. Einstein AJ, Henzlova MJ, Rajagopalan S. Estimating risk of cancer associated with radiation exposure from 64-slice computed tomography coronary angiography. *JAMA.* 2007;298(3):317-323.
22. Conference of Radiation Control Program Directors. *Nationwide Evaluation of X-Ray Trends (NEXT): Tabulation and Graphical Summary of 2000 Survey of Computed Tomography.* Frankfort, KY: Conference of Radiation Control Program Directors Inc; 2007.
23. Hunsaker AR, Zou KH, Poh AC, et al. Routine pelvic and lower extremity CT venography in patients undergoing pulmonary CT angiography. *AJR Am J Roentgenol.* 2008;190(2):322-326.
24. Twombly R. Full body CT screening: preventing or producing cancer. *J Natl Cancer Inst.* 2004;96(22):1650-1651.
25. Griffey RT, Sodickson A. Cumulative radiation exposure and cancer risk estimates in emergency department patients undergoing repeat or multiple CT. *AJR Am J Roentgenol.* 2009;192(4):887-892.
26. McBride J, Paxton B, Warddrop R. Majority of ordering physicians lack knowledge of radiation exposure risks from CT. Study presented at: 109th Annual American Roentgen Ray Society Meeting; April 27, 2009; Boston, MA.
27. Caoili EM, Cohan RH, Ellis JH, Dillman J, Schipper MJ, Francis IR. Medical decision making regarding computed tomographic radiation dose and associated risk: the patient's perspective. *Arch Intern Med.* 2009;169(11):1069-1071.
28. Greess H, Wolf H, Baum U, et al. Dose reduction in computed tomography by attenuation-based on-line modulation of tube current: evaluation of six anatomical regions. *Eur Radiol.* 2000;10(2):391-394.
29. Nagel HD, Blobel J, Brix G, et al. 5 years of "concerted action dose reduction in CT"–what has been achieved and what remains to be done? [in German]. *Rofo.* 2004;176(11):1683-1694.
30. Hausleiter J, Meyer T, Hermann F, et al. Estimated radiation dose associated with cardiac CT angiography. *JAMA.* 2009;301(5):500-507.
31. Arch ME, Frush DP. Pediatric body MDCT: a 5-year follow-up survey of scanning parameters used by pediatric radiologists. *AJR Am J Roentgenol.* 2008;191(2):611-617.
32. Brenner D, Elliston C, Hall E, Berdon W. Estimated risks of radiation-induced fatal cancer from pediatric CT. *AJR Am J Roentgenol.* 2001;176(2):289-296.
33. European Commission. *Referral Guidelines for Imaging: Radiation Protection 118.* Luxembourg: Office for Official Publications of the European Communities; 2001.
34. Canadian Association of Radiologists. *Diagnostic Imaging Referral Guidelines.* 2005. http://www.car.ca/content.aspx?pg=Guidelines&spg=Stds_GuideIns&lang=E&IID=. Accessed February 13, 2009.
35. Ficaro EP, Zanzonico P, Stabin MG, et al. Variability in radiation dose estimates from nuclear and computed tomography diagnostic imaging. American Society of Nuclear Cardiology, Guidelines and Standards Web site. http://www.asnc.org/content_184.cfm?tagSearch=true. Accessed September 1, 2009.
36. Hurwitz LM, Reiman RE, Yoshizumi TT, et al. Radiation dose from contemporary cardiothoracic multidetector CT protocols with an anthropomorphic female phantom: implications for cancer induction. *Radiology.* 2007;245(3):742-750.
37. Einstein AJ, Sanz J, Dellegrottaglie S, et al. Radiation dose and cancer risk estimates in 16-slice computed tomography coronary angiography. *J Nucl Cardiol.* 2008;15(2):232-240.
38. Berrington de González A, Darby SC. Risk of cancer from diagnostic x-rays: estimates for the UK and 14 other countries. *Lancet.* 2004;363(9406):345-351.