Original Investigation

The Use of Computed Tomography in Pediatrics and the Associated Radiation Exposure and Estimated Cancer Risk

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IMPORTANCE Increased use of computed tomography (CT) in pediatrics raises concerns about cancer risk from exposure to ionizing radiation.

OBJECTIVES To quantify trends in the use of CT in pediatrics and the associated radiation exposure and cancer risk.

DESIGN Retrospective observational study.

SETTING Seven US health care systems.

PARTICIPANTS The use of CT was evaluated for children younger than 15 years of age from 1996 to 2010, including 4 857 736 child-years of observation. Radiation doses were calculated for 744 CT scans performed between 2001 and 2011.

MAIN OUTCOMES AND MEASURES Rates of CT use, organ and effective doses, and projected lifetime attributable risks of cancer.

RESULTS The use of CT doubled for children younger than 5 years of age and tripled for children 5 to 14 years of age between 1996 and 2005, remained stable between 2006 and 2007, and then began to decline. Effective doses varied from 0.03 to 69.2 mSv per scan. An effective dose of 20 mSv or higher was delivered by 14% to 25% of abdomen/pelvis scans, 6% to 14% of spine scans, and 3% to 8% of chest scans. Projected lifetime attributable risks of solid cancer were higher for younger patients and girls than for older patients and boys, and they were also higher for patients who underwent CT scans of the abdomen/pelvis or spine than for patients who underwent other types of CT scans. For girls, a radiation-induced solid cancer is projected to result from every 300 to 390 abdomen/pelvis scans, 330 to 480 chest scans, and 270 to 800 spine scans, depending on age. The risk of leukemia was highest from head scans for children younger than 5 years of age at a rate of 1.9 cases per 10 000 CT scans. Nationally, 4 million pediatric CT scans of the head, abdomen/pelvis, chest, or spine performed each year are projected to cause 4870 future cancers. Reducing the highest 25% of doses to the median might prevent 43% of these cancers.

CONCLUSIONS AND RELEVANCE The increased use of CT in pediatrics, combined with the wide variability in radiation doses, has resulted in many children receiving a high-dose examination. Dose-reduction strategies targeted to the highest quartile of doses could dramatically reduce the number of radiation-induced cancers.

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The use of computed tomography (CT) in pediatrics has increased over the last 2 decades.[1-6] In 2011, 85 million CT scans were performed in the United States,[7] with 5% to 11% of these scans being performed on children.[3,8,9] Although the use of CT has greatly improved diagnostic capabilities, its use comes with risks. The ionizing radiation doses delivered by CT are 100 to 500 times higher than conventional radiography and are in ranges linked to an increased risk of cancer.[10,11] This is especially concerning for children because they are more sensitive to radiation-induced carcinogenesis and have many remaining years of life left for cancer to develop.[3,12,13] A recent study[14] in the United Kingdom found that children who received an active bone marrow dose from CT of 30 mGy or higher were at 3.2 times greater risk of leukemia and that children who received a brain dose of 50 mGy or higher were at 2.8 times greater risk of brain cancer.

A prior study[9] estimated that 4350 future cancers could be induced by 1 year of pediatric CT imaging in the United States; however, the study assumed that pediatric-specific settings were always used and did not model variability in dose. We found that radiation doses from CT for adults are higher and more variable than generally quoted.[1,15] Doses received by children have been less well studied,[16] and most studies have been in select populations such as trauma[17,18] or cancer patients.[19,20] Absorbed doses in children may be higher because of lower radiation attenuation in smaller patients[21] and may be more variable because CT technologists do not always adjust scanner settings based on a patient's age or size.[22-24] It is unknown whether recent recommendations to lower doses in children[25,26] have been widely implemented.

We examined trends in CT imaging among pediatric enrollees of 6 diverse health care systems and calculated radiation exposure and lifetime attributable risks of cancer from a random sample of CT scans. We projected the number of future cancers expected to result from the use of CT in pediatrics if national use reflects our observed patterns and if dose reduction strategies were implemented.

Methods

Our retrospective study was conduced within the HMO Research Network (http://www.hmoresearchnetwork.org/). We studied the use of CT for children 15 years of age or younger who were enrolled in any of 6 integrated health care systems: Group Health Cooperative in Washington; Kaiser Permanente Colorado, Georgia, Hawaii, and Northwest; and Marshfield Clinic in Wisconsin. We determined radiation doses from pediatric CT scans at 4 of these systems (Group Health, Kaiser Permanente Hawaii and Northwest, and Marshfield Clinic) plus the Henry Ford Health System in Michigan. Members reflected the diverse racial/ethnic and socioeconomic statuses of the areas served. Study methods were approved by each site's institutional review board.

The Use of CT

We evaluated the use of CT by using standardized data in the HMO Research Network's Virtual Data Warehouse.[27] We included 7 to 15 years of data from 1996 to 2010 from each health system. Children were included each year that they were continuously enrolled, plus years of birth or death. The CT scans were mapped to an anatomic target (head, abdomen/pelvis, chest, spine, or other/unknown) using *Current Procedural Terminology, Fourth Edition* codes; *International Classification of Diseases, Ninth Revision, Clinical Modification* codes; and Healthcare Common Procedure Coding System codes. Examinations with the same code performed on the same patient on the same day were treated as a single examination to avoid overcounting.

Radiation Dose From CT and Estimated Cancer Risk

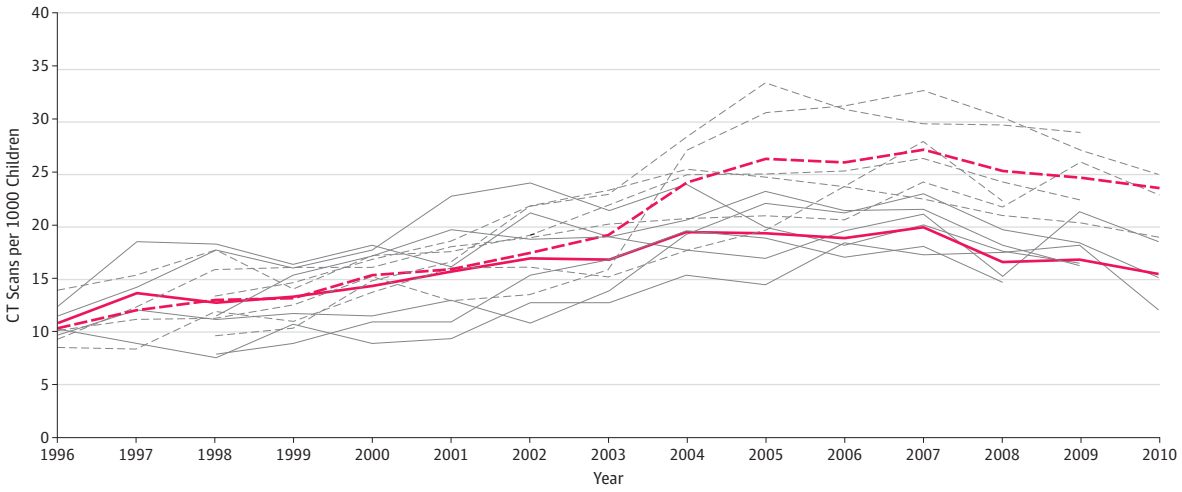
We calculated radiation dose from 744 pediatric CT scans of the head, chest, abdomen/pelvis, and spine. Examinations of these regions account for more than 95% of pediatric CT scans. Examinations were randomly selected within age-sex-year strata from 2001 to 2011, with data from a subset of years from some health systems. We abstracted scan parameters and estimated organ and effective doses using a novel dosimetry method[28] based on improved sex- and age-specific computational anatomy phantoms.[29-32] Details are provided in the eAppendix in the Supplement.

We estimated lifetime attributable risks of cancers from the observed organ doses using age- and sex-specific cancer risk models in the Biological Effects of Ionizing Radiations (BEIR) VII report (breast, colon, liver, lung, ovarian, prostate, stomach, thyroid, bladder, uterus, and leukemia)[10] and Berrington de González et al[9] (oral, esophagus, rectum, pancreas, kidney, and brain). These cancers account for 70% to 85% of incident cancers in the United States. Solid cancer risks were estimated from organ doses using a linear no-threshold dose-response model, but with a reduction in the resulting risk estimates by a dose and dose-rate effectiveness factor of 1.5.[10] Leukemia risk was estimated from red bone marrow doses using a linear-quadratic model.[10]

Statistical Analysis

We calculated annual rates of CT use by age group, anatomic region imaged, and health system and estimated average rates using marginal standardization. We calculated descriptive statistics of radiation doses and cancer risks. We assume that 4.25 million pediatric CT scans are performed in the United States each year based on an estimated 85 million overall CT scans performed in the United States in 2011,[7] and we estimate that 5% of these CT scans are performed on children, which is the lower end of the range of 5% to 11% reported in the literature.[3,8,9] We estimated the number of head, abdomen/pelvis, chest, and spine scans by age from our population's distribution. We projected the number of radiation-induced cancers from these pediatric CT scans using the lifetime attributable risks corresponding to the observed organ doses. We also projected the number of radiation-induced cancers under 2 scenarios: (1) if the number of CT scans of each type were reduced by one-third (estimated number of unnecessary scans[3,33]) and (2) if doses above the 75th percentile were lowered to the median observed dose (within age group and anatomic region). We estimated 95% uncertainty limits for the

Figure 1. Trends in the Use of Computed Tomography (CT) Over Time, by Age Group and Health Care System



The solid lines show rates for children younger than 5 years of age; the dashed lines show rates for children 5 to 14 years of age. The gray lines show rates at each health system, and the red lines show the average rates across health systems.

number of solid cancers and leukemia cases using the coefficients of variation reported in the BEIR-VII report.[10]

Results

The Use of CT

Between 152 419 and 371 095 children were included each year for a total of 4 857 736 child-years of observation. Half were girls, and 29% were younger than 5 years of age. The use of CT increased between 1996 and 2005, remained stable between 2005 and 2007, and then began to decline (**Figure 1**). Rates were similar for children younger than 5 years of age and children 5 to 14 year of age from 1996 to 2003, and then they diverged, with a greater increase in the number of scans among older children (Figure 1). Among children younger than 5 years of age, the use of CT doubled from 11 scans per 1000 children in 1996 to 20 scans per 1000 children between 2005 and 2007, and then it decreased to 15.8 scans per 1000 children in 2010. For children 5 to 14 years of age, the use of CT almost tripled from 10.5 scans per 1000 children in 1996 to 27.0 scans per 1000 children between 2005 and 2007, before decreasing to 23.9 scans per 1000 children in 2010. Trends were similar across health care systems, with greater variability in rates of CT use for younger children in earlier years and for older children in recent years (Figure 1).

The use of CT increased through 2005 for each anatomic area studied; however, the increase was greatest for abdomen/pelvis scans for children 5 to 14 years of age (**Figure 2**), increasing from 2.0 scans per 1000 children in 1996 to a peak of 10.8 scans per 1000 children in 2007, then decreasing to 9.1 scans per 1000 children in 2010. The increase in the number of abdomen/pelvis scans was much lower for children younger than 5 years of age, increasing from 2.1 scans per 1000 children in 1996 to a peak of 3.9 scans per 1000 children in 2007, then decreasing to 2.9 scans per 1000 children in 2010. The head was the most commonly scanned region for both age groups, increasing by approximately 50% from 1996 to 2010. From 1996 to 2010, the number of chest scans also increased by 50%, while the number of spine scans increased 4- to 9-fold.

Radiation Dose and Associated Cancer Risk

Effective doses were highest for abdomen/pelvis scans, with the mean dose increasing from 10.6 mSv among children younger than 5 years of age to 14.8 mSv among children 10 to 14 years of age (**Table 1**). Effective doses also tended to increase with advancing age for chest and spine scans but decreased with age for head scans (Table 1). An effective dose of 20 mSv or higher was delivered by 14% to 25% of abdomen/pelvis scans, 3% to 8% of chest scans, and 6% to 14% of spine scans, depending on age.

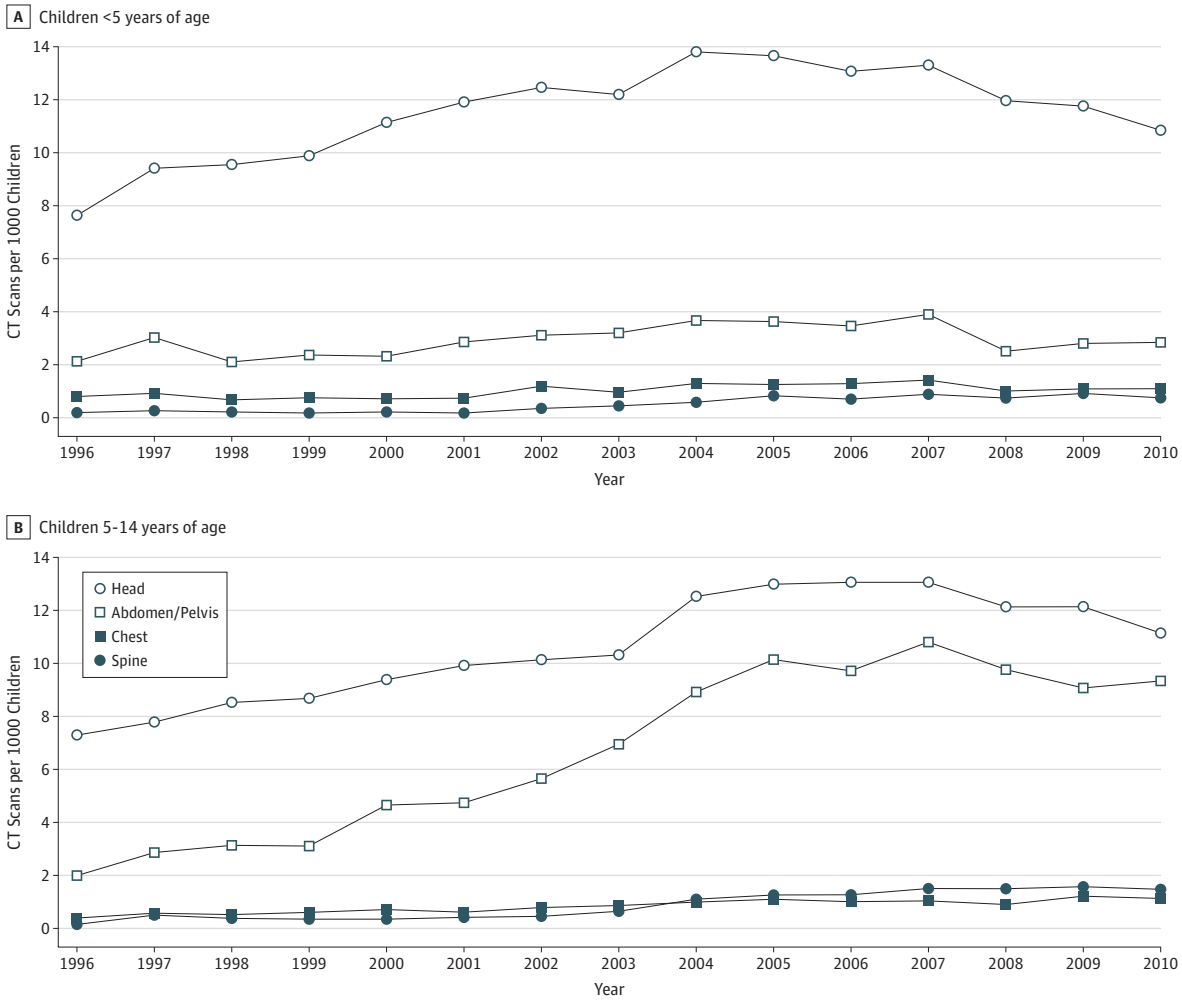
Organ Doses

Mean organ doses show an expected pattern of exposure (eg, brain doses are highest for head scans; breast, lung, and esophagus doses are highest for chest scans; Table 1). Distributions for doses to the brain, red bone marrow, thyroid, breast, lung, and colon wall by age group and anatomic region imaged are shown in eFigure 1 in the Supplement. For head scans, 7% of the scans for children younger than 5 years of age, 8% of the scans for children 5 to 9 years of age, and 14% of the scans for children 10 to 14 years of age gave a brain dose of 50 mGy or higher (eFigure 1 [Supplement]). Among girls, breast doses are highest for chest, abdomen/pelvis, and spine scans. Abdomen/pelvis scans delivered relatively high doses for many radiosensitive organs such as the breast and colon. Active bone marrow doses are highest for head scans for children younger than 10 years of age and abdomen/pelvis scans for children 10 to 14 years of age.

Solid Cancer Risks

The projected lifetime attributable risk of solid cancer decreased with advancing age for head and spine scans, with a less con-

Figure 2. Trends in the Use of Computed Tomography (CT) Over Time, by Age Group and Anatomic Area Imaged



sistent relationship for abdomen/pelvis and chest scans (**Table 2**). Solid cancer risks were higher for girls than boys and tended to be highest for abdomen/pelvis scans, with 25.8 to 33.9 projected cases per 10 000 CT scans for girls vs 13.1 to 14.8 cases per 10 000 CT scans for boys (Table 2). A radiation-induced solid cancer is projected to result from every 300 to 390 abdomen/pelvis scans for girls and from every 670 to 760 abdomen/pelvis scans for boys. Solid cancer risk was also high for chest and spine scans for girls, with 1 case projected to result from every 330 to 480 chest scans and from every 270 to 800 spine scans, depending on age. Solid cancer risk was lowest for head scans for children 5 years of age and older, at 1.1 to 2.4 cases per 10 000 CT scans.

Leukemia Risks

The projected lifetime attributable risk of leukemia was highest for head scans among children younger than 10 years of age and decreased with age from 1.9 cases per 10 000 scans for children younger than 5 years of age to 0.5 cases per 10 000 scans for children 10 to 14 years of age. For children 10 to 14 years of age, the risk of leukemia was highest for abdomen/pelvis scans at 1.0 cases per 10 000 scans. A case of leukemia was projected to result from 1 in 5250 head scans performed for children younger than 5 years of age and from 1 in 21 160 scans for children 10 to 14 years of age. The risk of leukemia was 0.8 to 1.0 cases per 10 000 abdomen/pelvis scans and 0.4 to 0.7 cases per 10 000 chest and spine scans (Table 2).

Projected Radiation-Induced Cancers From CT Use in Pediatrics

Conservatively assuming that 4.25 million pediatric CT scans are performed each year in the United States, 4.0 million CT scans would be of the head, abdomen/pelvis, chest, or spine based on our observed distribution. If radiation doses from those CT scans parallel our observed dose distributions, approximately 4870 future cancers (95% uncertainty limit, 2640-9080 future cancers) could be induced by pediatric CT scans each year (**Table 3**). Cases of breast, thyroid, and lung cancers and cases of leukemia account for 68% of projected cancers in exposed girls (eFigure 2 [Supplement]), whereas cases of brain, lung, and colon cancers and cases of leukemia account for 51% of future cancers in boys (eFigure 2 [Supplement]). Reducing the highest 25% of doses within age groups and anatomic re-

Table 1. Distribution of Effective Doses and Mean Organ Doses from Computed Tomography by Anatomic Region and Patient Age[a]

	Head			Abdomen/Pelvis			Chest			Spine		
	<5 y	5-9 y	10-14 y	<5 y	5-9 y	10-14 y	<5 y	5-9 y	10-14 y	<5 y	5-9 y	10-14 y
Patients, No.	98	79	102	72	89	115	52	37	58	10	14	18
Effective dose, percentile												
Mean	3.5	1.5	1.1	10.6	11.1	14.8	5.3	7.5	6.4	5.8	7.7	8.8
25th	1.4	0.5	0.6	3.2	3.5	6.4	2.5	2.6	3.1	0.6	1.5	2.5
50th	2.6	1.2	1.0	4.7	8.0	11.1	3.1	3.9	5.3	2.9	4.1	5.3
75th	4.8	2.0	1.6	14.4	14.8	20.0	4.8	10.5	8.6	6.3	10.5	10.3
95th	11.2	3.2	2.6	30.2	32.9	35.0	20.5	26.1	18.4	26.6	26.7	42.0
Dose ≥20 mSv, % of patients	0.0	0.0	0.0	13.9	15.7	25.2	5.8	8.1	3.4	10.0	14.3	5.6
Mean organ dose, mGy												
Brain	28.8	25.3	29.8	0.1	0.1	0.1	0.3	0.4	0.3	0.8	1.1	0.7
Thyroid	11.8	1.2	1.0	1.0	0.6	0.6	11.4	17.5	13.6	10.8	11.4	6.4
Esophagus	3.7	0.6	0.4	5.1	5.2	6.9	8.4	12.4	10.3	8.4	7.6	8.5
Lungs	1.9	0.4	0.3	7.6	6.2	8.1	10.2	15.0	13.2	7.7	7.1	9.7
Breast	0.9	0.1	0.1	14.8	13.0	14.0	7.8	10.6	9.9	8.3	13.0	9.7
Stomach wall	0.7	0.1	0.0	15.9	18.1	25.3	6.1	8.7	8.0	7.5	14.5	17.9
Liver	0.8	0.1	0.0	16.3	18.0	25.3	6.9	9.9	8.9	8.6	14.9	20.3
Colon wall	0.3	0.0	0.0	16.0	18.8	26.2	2.3	2.7	2.2	3.6	5.9	4.7
Rectosigmoid wall	0.1	0.0	0.0	12.1	13.8	16.7	0.7	0.6	0.2	1.0	1.2	0.7
Bladder wall	0.1	0.0	0.0	13.0	14.6	16.6	0.7	0.4	0.1	0.7	0.7	0.4
Prostate	0.1	0.0	0.0	9.0	10.1	11.0	0.7	0.1	0.1	0.1	0.1	0.2
Uterus	0.1	0.0	0.0	12.6	13.5	16.9	0.4	0.6	0.1	1.2	1.5	0.2
Ovaries	0.1	0.0	0.0	14.6	15.4	19.6	0.5	0.7	0.1	1.8	1.8	0.2
Red bone marrow	10.6	6.5	4.2	5.1	5.6	9.2	3.3	3.9	3.6	4.4	3.0	3.9

[a] The doses to the breast, uterus, and ovaries are for girls only; the doses to the prostate are for boys only.

Table 2. Lifetime Attributable Risk of Solid Cancer and Leukemia From CT and Number of CT Scans Leading to 1 Case of Cancer

	Head Scan			Abdomen/Pelvis Scan			Chest Scan			Spine Scan		
	Solid Cancer			Solid Cancer			Solid Cancer			Solid Cancer		
Age, y	Girls	Boys	Leukemia	Girls	Boys	Leukemia	Girls	Boys	Leukemia	Girls	Boys	Leukemia
Lifetime Attributable Risk of Cancer per 10 000 CT Scans												
<5	17.5	7.4	1.9	33.9	14.8	0.8	28.4	8.4	0.6	37.5	5.3	0.7
5-9	1.6	2.4	0.9	25.8	13.7	0.7	30.5	9.2	0.5	26.2	7.9	0.4
10-14	1.1	2.1	0.5	27.2	13.1	1.0	20.9	6.1	0.4	12.5	8.6	0.5
No. of CT Scans Leading to 1 Case of Cancer (Rounded to the Nearest 10)												
<5	570	1350	5250	300	670	12 170	350	1190	17 470	270	1890	14 630
5-9	6130	4150	11 660	390	730	14 470	330	1080	20 570	380	1260	26 940
10-14	9020	4660	21 160	370	760	10 380	480	1650	25 430	800	1170	22 020

Abbreviation: CT, computed tomography.

gions to the median dose could prevent 2090 (43%) of these cancers, compared with a 33% reduction in future cancers if a third fewer CT scans were performed (Table 3). Combining these 2 strategies could prevent 3020 (62%) of these cancers.

Discussion

Among several diverse integrated health care systems, and using an improved dosimetry method that accounts for children's smaller body size, we found that many children received high radiation doses from CT associated with a small but significant increase in future cancer risk. This is due to both the greater use of higher-dose CT types, such as abdomen and pelvis scans, and the wide variability in radiation doses delivered for each examination. Up to a quarter of children with a single abdomen/pelvis scan received a dose of 20 mSv or higher. We project that a radiation-induced cancer could result from every 300 to 390 abdomen/pelvis scans performed for girls. Brenner and colleagues[12] estimated 1 in 550 abdomen and pelvis scans might result in a future cancer death based on pediatric organ doses approximated from published doses for adults.

Table 3. Projected Number of Future Radiation-Induced Cancers That Could Be Related to the Most Commonly Performed Pediatric CT Scans in the United States Under 3 Scenarios

CT Scan	Estimated No. of Pediatric Scans[a]	Projected No. of Future Radiation-Induced Cancers Related to Pediatric CT Use[b]								
		Scenario 1[c]			Scenario 2[d]			Scenario 3[e]		
		Solid Cancer	Leukemia	Total (95% UL)	Solid Cancer	Leukemia	Total (95% UL)	Solid Cancer	Leukemia	Total (95% UL)
Head	2.2	1000	210	1210 (630-2370)	670	140	810 (420-1580)	470	160	630 (320-1280)
Abdomen/pelvis	1.4	2810	110	2930 (1600-5360)	1880	80	1950 (1070-3600)	1660	70	1730 (950-3180)
Chest	0.2	340	10	350 (190-640)	230	10	230 (130-440)	200	10	210 (110-390)
Spine	0.2	370	10	390 (210-690)	250	10	260 (140-480)	210	10	210 (120-410)
Total	4.0	4530	340	4870 (2640-9080)	3020	230	3250 (1760-6060)	2540	240	2780 (1500-5220)

Abbreviations: CT, computed tomography; UL, uncertainty limit.

[a] In the millions.

[b] The numbers of cancers are rounded to the nearest 10.

[c] Doses reflect those observed in clinical practice.

[d] Number of CT scans reduced by one-third.

[e] Doses above the 75th percentile are lowered to median observed dose.

We projected the risk of radiation-induced cancers from the organ doses that we observed and from the BEIR-VII[10] and Berrington de González et al[9] risk models. These risk projections are only estimates based on the best available evidence and are in no way definitive. These models rely on analysis of data from the Life Span Study of Japanese atomic bomb survivors. The application of increased risks observed in the Life Span Study to radiation from CT scanners has been criticized by some owing to differences in the source of radiation, the population exposed, and the assumption of a linear-no-threshold association. However, a recent study[14] found a direct association between pediatric CT and increased risk of both leukemia and brain cancer of similar magnitude as the Life Span Study, providing additional evidence of the validity of applying these cancer risk projections to doses from CT imaging. Specifically, Pearce and colleagues[14] found that children who received a cumulative brain dose of at least 50 mGy were at 2.8 times greater risk of brain cancer. In our study, 7% to 14% of head scans had brain doses in this range from a single examination. And many children who undergo CT receive multiple scans.[34]

Nationally, if radiation doses from CT reflect the wide distribution that we observed, then 1 year of CT imaging for children younger than 15 years of age might induce 4870 future cancers. This number is slightly higher than the number estimated for children younger than 18 years of age in a prior study,[9] which assumed that pediatric-specific settings were used for all CT scans and did not account for variability in dose (which we found was substantial). The number of radiation-induced cancers could be greatly decreased if dose-reduction strategies were implemented. Diagnostic reference levels are traditionally set at the 75th percentile of the dose distribution; doses above that level need to be justified or reduced.[35,36] The use of diagnostic reference levels has successfully lowered doses from CT in the United Kingdom.[37] We estimated the potential impact of lowering the top 25% of doses to the median, which could be achieved by implementing standardized pediatric CT protocols, such as those found on the Image Gently website,[38] and other guidelines for ensuring that doses are "as low as reasonably achievable."[39,40] We found that 43% of the projected future cancers associated with pediatric CT might be prevented. We estimate that reducing the highest 50% of doses to the median would only prevent another 8% of cancers; thus, the biggest potential gains come from focusing on the highest 25% of doses.

The use of CT on older children nearly tripled from 1996 to 2005 to a peak of 27 CT scans per 1000 children. This relative increase is similar to that observed among enrollees of all ages in the same population.[1] The increase in use was lower among younger children, with a doubling of use during the same time period to 20 CT scans per 1000 children. The use of CT in our study population has stabilized and slightly declined since 2007, particularly among younger children. This decline may be the result of increased awareness about the cancer risks from pediatric imaging,[12,22,23,25,41,42] in part due to the "Image Gently" campaign started in 2007.[26] Notably, the rates of CT use in this population of HMO enrollees are lower than the rates of 27 to 29 CT scans per 1000 children among children younger than 5 years of age and the rates of 32 to 57 CT scans per 1000 children among children 5 to 14 years of age reported for 5 large regional markets of UnitedHealthcare during a similar time period,[34] which suggests that CT may be more frequently used in the fee-for-service environment.

From a patient's perspective, the benefits of a medically necessary CT scan far exceed the small increase in radiation-induced cancer risk. However, some studies[3,33] suggest that a third of pediatric CT scans are unnecessary and that eliminating them could potentially reduce the number of CT-attributable cancers by a third. Combining the 2 strategies of reducing unnecessary scans and reducing the highest 25% of doses could potentially prevent 62% of the projected radiation-related cancers. Thus, more research is urgently needed to determine when CT in pediatrics can lead to improved health outcomes and whether other imaging methods (or no imaging) could be as effective. For now, it is important for both the referring physician and the radiologist to consider whether the risks of CT exceed the diagnostic value it provides over other tests, based on current evidence.[43]

The risk of radiation-induced solid cancer is highest for the abdomen/pelvis scan, which has seen the most dramatic increase in use, especially among older children. Among the abdomen/pelvis scans included in our dose calculations, most were for pain (40%), possible appendicitis (11%), or infection (6%) (eTable 1 [Supplement]). Ultrasonography is a reasonable alternative for assessing appendicitis because its accuracy is high and it does not use ionizing radiation. Evidence supports limiting pediatric CT use in this setting to patients with equivocal or negative findings on ultrasonography.[44-47] The risks of radiation-induced leukemia and brain cancer are highest for head scans, which are the most commonly performed CT scans in pediatrics. Although the effective dose for a head scan is relatively low, the brain and red bone marrow doses are relatively high, especially for young children, resulting in the highest risks of brain cancer and leukemia. Among the head scans included in our dose estimation, most were to evaluate trauma (23%), upper respiratory issues (22%), or headache (17%) (eTable 2 [Supplement]). Recent guidelines suggest that the use of head scans for trauma can be reduced when highly sensitive prediction rules are used to determine which patients truly need imaging.[48] The effectiveness of head scans for headache or sinusitis in pediatrics has not been sufficiently studied to know its value.

A strength of our study is that we collected technical parameters used in examinations from diverse facilities and CT machines to estimate the distribution of radiation doses. Our dose calculations accounted for patient size and sex using an improved dosimetry method. Because of the HMO Research Network infrastructure, we had complete capture of health care utilization from diverse sites across the United States.

Our primary study limitations are that we could not evaluate the appropriateness of imaging or examine changes in radiation doses over time (because of differences in study years across sites). For inpatient procedures, only the admission date was available; thus, collapsing multiple procedures performed on the same day could undercount the number of scans. Our risk projections are likely conservative because they only include cancers with published models,[9,10] which excludes 15% to 30% of incident cancers, depending on age and sex. In addition, our projections are lower than those recently made available via an online tool,[49] which uses a slightly different method than that of the BEIR-VII report. The challenge of projecting cancer risk is quantifying the uncertainty due to statistical variation in the model parameter estimates, the method used to transport risk estimates from the Japanese to the US population and the choice of dose and dose-rate effectiveness factor used to adjust downward the risk estimates from the linear no-threshold model. Our 95% uncertainty limits around the projected numbers of cancers are based on the coefficients of variation given in the BEIR-VII report,[10] which provides a gross variability estimate from these 3 sources of uncertainty.

In conclusion, the use of CT in pediatrics has increased sharply since 1996, especially for older children, but has started to decrease in the past few years. The limited evidence about the appropriateness of most CT procedures, particularly for children, makes it difficult to know how much further the rates should be reduced. Perhaps more importantly, we found that radiation doses from pediatric CT vary widely in clinical practice, suggesting an opportunity to reduce doses through standardized protocols and other published methods.[26,39,40] Implementation of these readily available dose-reduction strategies, combined with the elimination of unnecessary imaging, could dramatically reduce future radiation-induced cancers from CT use in pediatrics.

ARTICLE INFORMATION

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