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Pediatric Computed Tomography and Associated Radiation Exposure and Estimated Cancer Risk

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Abstract

Objectives—To quantify trends in pediatric computed tomography (CT) use and associated radiation exposure and cancer risk.

Design—Retrospective observational study.

Setting—Seven US healthcare systems.

Participants—CT use was evaluated in children <15 years from 1996-2010, including 4,857,736 child-years of observation. Radiation doses were calculated for 744 CT scans performed between 2001-2011.

Outcome Measures—Rates of CT use, organ and effective doses, and projected lifetime attributable cancer risks.

Results—CT use doubled in children <5 years and tripled in children 5-14 between 1996-2005, stabilized until 2007, then declined. Effective doses varied from 0.03-69.2mSv per scan. An effective dose of ≥20mSv was delivered by 14-25% of abdomen/pelvis CTs, 6-14% of spine CTs,

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and 3-8% of chest CTs. Projected lifetime attributable risks of solid cancer were higher in younger patients and girls, and for abdomen/pelvis and spine CTs. In girls, a radiation-induced solid cancer is projected to result from every 300-390 abdomen/pelvis CTs, 330-480 chest CTs, and 270-800 spine CTs, depending on age. Leukemia risk was highest for head CTs in children <5 at 1.9/10,000. Nationally, 4 million pediatric CTs 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—Increased use of pediatric CT combined with 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.

INTRODUCTION

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

A prior study estimated that 4,350 future cancers could be induced by one year of pediatric CT imaging in the US; however, the study assumed that pediatric-specific settings were always used and did not model variability in dose.[9] We found that radiation doses from CT in 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 patient 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 six diverse healthcare systems and calculated radiation exposure and lifetime attributable cancer risks from a random sample of CTs. We projected the number of future cancers expected to result from pediatric CT if national use reflects our observed patterns and if dose reduction strategies were implemented.

METHODS

This retrospective study was conduced within the HMO Research Network (HMORN; http://www.hmoresearchnetwork.org/). We studied CT utilization among children aged 15 years or younger enrolled in any of six integrated healthcare systems: Group Health Cooperative in Washington; Kaiser Permanente Colorado, Georgia, Hawaii, and Northwest; and Marshfield Clinic in Wisconsin. We determined radiation doses from pediatric CTs at four of these systems (Group Health, Kaiser Permanente Hawaii and Northwest, and Marshfield Clinic) plus Henry Ford Health Systems in Michigan. Members reflected the diverse racial/ethnic and socioeconomic statuses of the areas served. Study methods were approved by each sites's institutional review board.

CT Utilization

We evaluated CT utilization using standardized data in the HMORN's Virtual Data Warehouse (VDW).[27] We included 7-15 years of data from 1996-2010 from each health system. Children were included each year they were continuously enrolled, plus years of birth or death. CTs were mapped to an anatomic target (head, abdomen/pelvis, chest, spine, or other/unknown) using CPT-4, ICD-9-CM, and HCPCS codes. Examinations with the same code performed on the same patient on the same day were treated as a single examination to avoid over-counting.

Radiation Dose from CT and Estimated Cancer Risk

We calculated radiation dose from 744 pediatric CTs of the head, chest, abdomen/pelvis, and spine. Exams of these regions account for over 95% of pediatric CTs. Exams were randomly selected within age-gender-year strata from 2001-2011, 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 gender- and age-specific computational anatomy phantoms.[29, 30] Details are provided in eAppendix.

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, et al.[9] (oral, esophagus, rectum, pancreas, kidney, and brain). These cancers account for 70-85% of incident cancers in the US. 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 (DDREF) of 1.5.[10] Leukemia risk was estimated from red bone marrow doses using a linear-quadratic model.[10]

Statistical Analysis

We calculated annual CT rates 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 assumed 4.25 million pediatric CTs are performed in the US each year based on an estimated 85 million CTs performed among all ages in the US in 2011[7] and estimate of 5% of these exams performed in children, the lower end of the range of 5-11% reported in the literature.[3, 8, 9] We estimated the number of head, abdomen/pelvis, chest, and spine CTs by age from our population's distribution. We projected the number of radiation-induced cancers from these pediatric CTs using the lifetime attributable risks corresponding to the observed organ doses. We also projected the number of radiation-induced cancers under two scenarios: (1) if the number of CT exams of each type were reduced by 1/3 (estimated number of unnecessary exams[3, 31]) 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 number of solid cancers and leukemia cases using the coefficients of variation reported the BEIR-VII report.[10]

RESULTS

CT utilization

Between 152,419 and 371,095 children were included each year for a total of 4,857,736 child-years of observation. Half were female and 29% were <5 years of age. CT use increased between 1996-2005, remained stable between 2005-2007, and then began to decline (Figure 1). Rates were similar for children <5 and children 5-14 from 1996-2003, then diverged, with greater growth in imaging for older children (Figure 1). Among children

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<5, CT use doubled from 11/1000 in 1996 to 20/1000 in 2005-2007, then decreased to 15.8/1000 in 2010. In children 5-14, CT use almost tripled from 10.5/1000 in 1996 to 27.0/1000 in 2005-2007, before decreasing to 23.9/1000 in 2010. Trends were similar across healthcare systems, with greater variability in imaging rates for younger children in earlier years and for older children in recent years (Figure 1).

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

Radiation Dose and Associated Cancer Risk

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

Organ doses—Mean organ doses show an expected pattern of exposure (e.g., brain doses are highest for head CTs; breast, lung and esophagus doses are highest for chest CTs; 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. For head CTs, 7% of scans in children <5, 8% of scans in children 5-9, and 14% of scans in children 10-14 gave a brain dose of 50 mGy or higher (eFigure 1). Among girls, breast doses are highest for chest, abdomen/pelvis, and spine CTs. Abdomen/pelvis CTs delivered relatively high doses for many radiosensitive organs such as the breast and colon. Active bone marrow doses are highest for head CTs in children <10 and abdomen/pelvis CTs for children 10-14.

Solid cancer risks—The projected lifetime attributable risk of solid cancer decreased with advancing age for head and spine CT, with a less consistent relationship for abdomen/pelvis and chest CT (Table 2). Solid cancer risks were higher for girls and tended to be highest for abdomen/pelvis CTs, with 25.8-33.9 projected cases per 10,000 CT scans in girls versus 13.1-14.8 cases per 10,000 scans of boys (Table 2). A radiation-induced solid cancer is projected to result from every 300-390 abdomen/pelvis CTs in girls and every 670-760 CTs in boys. Solid cancer risk was also high for chest and spine CTs in girls, with one case projected to result from every 330-480 chest CTs and every 270-800 spine CTs, depending on age. Solid cancer risk was lowest for head CTs in children 5 and older, at 1.1-2.4 cancers per 10,000 CTs.

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

Projected Radiation-Induced Cancers from Pediatric CT in the US

Conservatively assuming that 4.25 million pediatric CTs are performed each year in the US, 4.0 million CTs would be of the head, abdomen/pelvis, chest, or spine based on our observed distribution. If radiation doses from those CTs parallel our observed dose distributions, approximately 4870 future cancers (95% uncertainty limits=2640-9080) could be induced by pediatric CT each year (Table 3). Breast, thyroid, and lung cancer and leukemia account for 68% of projected cancers in exposed girls (eFigure 2); whereas brain, lung, and colon cancer and leukemia account for 51% of future cancers in boys (eFigure 2). Reducing the highest 25% of doses within age groups and anatomic regions to the median dose could prevent 2090 (43%) of these cancers, compared to a 33% reduction in future cancers if a third fewer exams were performed (Table 3). Combining these two strategies could prevent 3020 (62%) of these cancers.

COMMENT

Among several diverse integrated healthcare 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 greater use of higher-dose CT types such as abdomen and pelvis CT, and wide variability in radiation doses delivered for each examination. Up to a quarter of children with a single abdomen/pelvis CT received a dose ≥20mSv. We project that a radiation-induced cancer could result from every 300-390 abdomen/pelvis CTs performed in girls. Brenner and colleagues[12] estimated 1 in 550 abdomen and pelvis CTs might result in a future cancer death based on pediatric organ doses approximated from published doses for adults.

We projected the risk of radiation-induced cancers from organ doses we observed and the BEIR-VII[10] and Berrington *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 due to differences in the source of radiation, the population exposed, and the assumption of a linear-no-threshold association. However, a recent study 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.[14] Specifically, Pearce and colleagues found that children who received a cumulative brain dose of at least 50 mGy were at 2.8 times greater risk of brain cancer.[14] In our study, 7-14% of head CTs had brain doses in this range from a *single* examination. And many children who receive a CT receive multiple CTs.[32]

Nationally, if radiation doses from CT reflect the wide distribution we observed, one year of CT imaging in children <15 might induce 4870 future cancers. This number is slightly higher than the number estimated for children <18 in a prior study,[9] which assumed pediatric-specific settings were used for all CTs 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.[33, 34] The use of diagnostic reference levels has successfully lowered doses from CT in the UK.[35] 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 ImageGently website,[36] and other guidelines for ensuring doses are “as low as reasonably achievable” (ALARA);[37, 38] 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.

CT use in older children nearly tripled from 1996 to 2005 to a peak of 27/1000. This relative increase is similar to that observed among enrollees of all ages in the same population.[1] Growth in use was lower in younger children, with a doubling of use during the same time period to 20/1000. CT imaging 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 cancer risks from pediatric imaging,[12, 22, 23, 25, 39, 40] in part due to the "Image Gently" campaign started in 2007.[26] Notably, the CT rates in this population of HMO enrollees are lower than rates of 27-29/1000 among children <5 years and 32-57/1000 among children 5-14 years reported for five large regional markets of UnitedHealthcare during a similar time period, [32] suggesting imaging use in the fee-for-service environment may be higher.

From a patient's perspective, the benefits of a medically necessary CT exam far exceed the small increase in radiation-induced cancer risk. However, some suggest that a third of pediatric CTs are unnecessary[3, 31] and eliminating these exams could potentially reduce the number of CT-attributable cancers by a third. Combining the two strategies of reducing unnecessary exams 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 pediatric CT leads to improved health outcomes and when other imaging (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.[41]

The risk of radiation-induced solid cancer is highest for abdomen/pelvis CT, 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%) (eTable1). Ultrasound is a reasonable alternative for assessing appendicitis, as 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 ultrasound findings.[42-45] The risk of radiation-induced leukemia and brain cancer are highest for head CT, which is the most commonly performed pediatric CT. Although the effective dose for head CT is relatively low, the brain and red bone marrow doses are relatively high, especially in young children, resulting in the highest risks of brain cancer and leukemia. Among the head CTs included in our dose estimation, most were to evaluate trauma (23%); upper respiratory issues (22%); or headache (17%) (eTable2). Recent guidelines suggest the use of head CT for trauma can be reduced when highly sensitive prediction rules are used to determine which patients truly need imaging.[46] The effectiveness of pediatric head CT for headache or sinusitis 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 gender using an improved dosimetry method. Because of the HMORN infrastructure, we had complete capture of healthcare utilization from diverse sites across the US.

Our primary study limitations are that we could not evaluate 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 exams. Our risk projections are likely conservative, because they only include cancers with published models,[9, 10] which excludes 15-30% of incident cancers, depending on age and gender. In addition, our projections are lower than those recently made available via an online tool[47], which uses a slightly different methodology than the BEIR-VII report. A challenge of projecting cancer risk is quantifying uncertainty from 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 DDREF used to downward-adjust 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 three sources of uncertainty.

CONCLUSION

Pediatric CT utilization has increased sharply since 1996, especially in 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, 37, 38] Implementation of these readily available dose-reduction strategies combined with eliminating unnecessary imaging could dramatically reduce future radiation-induced cancers from pediatric CT imaging.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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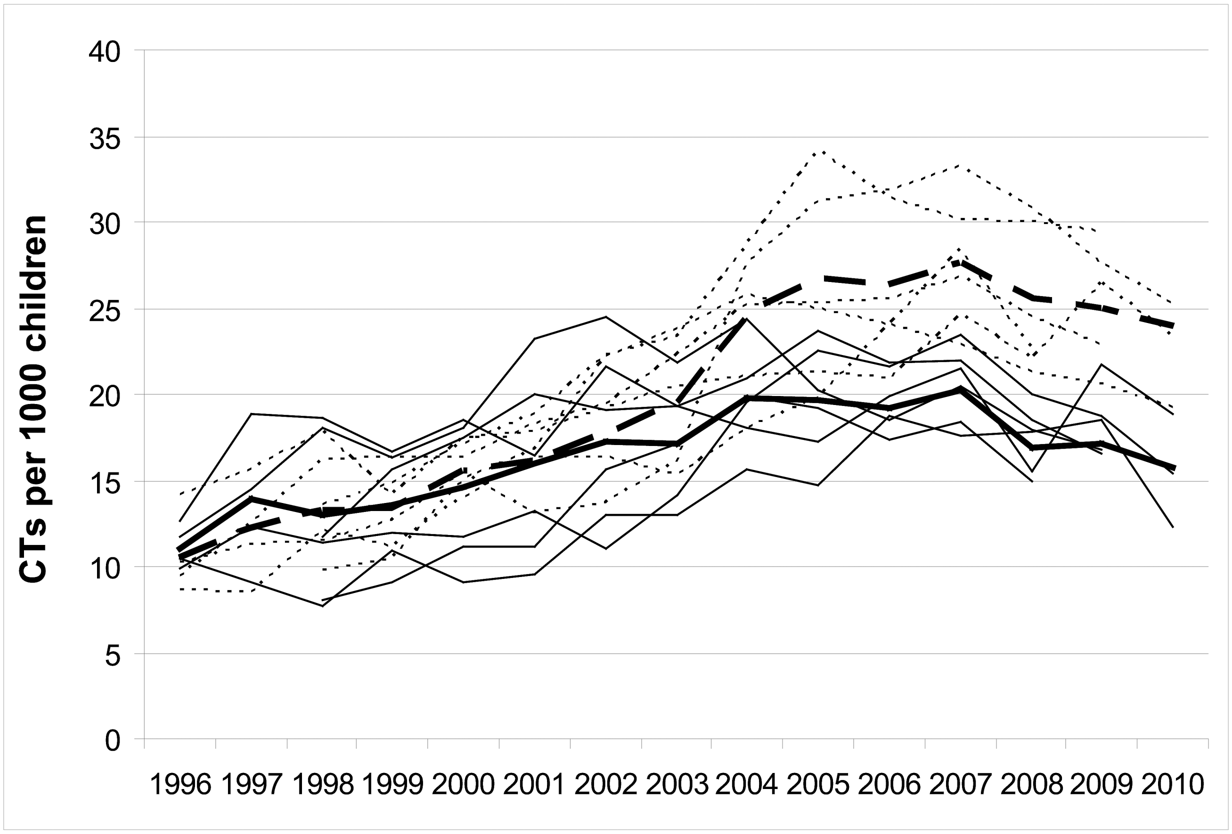

Figure 1. Trends in computed tomography (CT) use over time, by age group and health care system

Solid lines show rates for children <5 years; dashed lines show rates for children aged 5-14 years. Thin lines show rates at each health system and thick lines show the average rates across health systems.

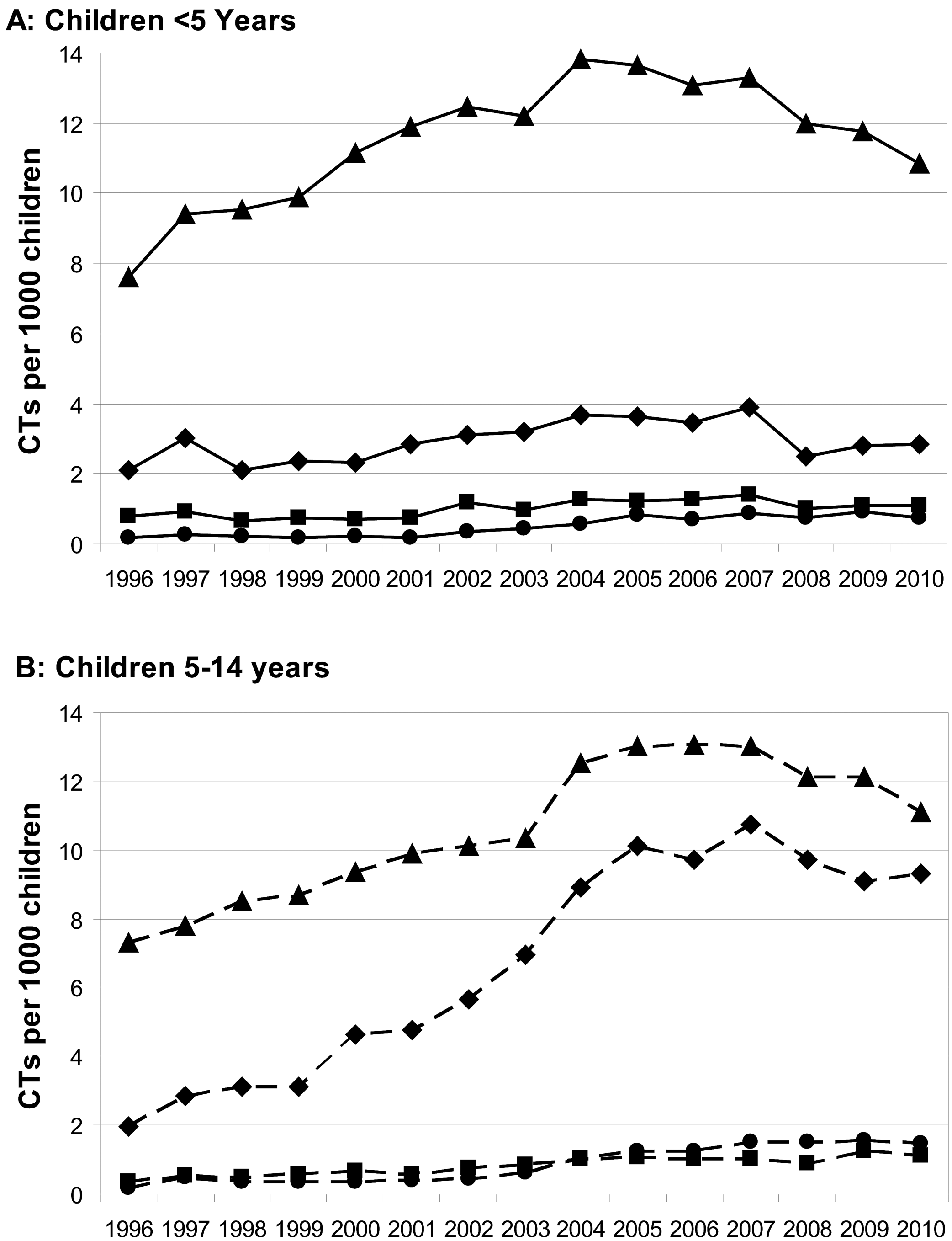

Figure 2.
Trends in computed tomography (CT) use over time, by age group and anatomic area imaged.

Table 1

Distribution of effective dose and mean organ doses from computed tomography by anatomic region and patient age. Breast, uterus, and ovaries doses are for girls only. Prostate doses are for boys only.

	N	Effective Dose, mSv						Mean Organ Doses, mGy													
		Mean	Percentile				Percent ≥20mSv	Brain	Thyroid	Esophagus	Lungs	Breast	Stomach wall	Liver	Colon wall	Recto-sigmoid wall	Bladder wall	Prostate	Uterus	Ovaries	Red bone marrow
Age (years)			25th	50th	75th	95th															
Head																					
<5	98	3.5	1.4	2.6	4.8	11.2	0.0%	28.8	11.8	3.7	1.9	0.9	0.7	0.8	0.3	0.1	0.1	0.1	0.1	0.1	10.6
5-9	79	1.5	0.5	1.2	2.0	3.2	0.0%	25.3	1.2	0.6	0.4	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	6.5
10-14	102	1.1	0.6	1.0	1.6	2.6	0.0%	29.8	1.0	0.4	0.3	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	4.2
Abdomen/Pelvis																					
<5	72	10.6	3.2	4.7	14.4	30.2	13.9%	0.1	1.0	5.1	7.6	14.8	15.9	16.3	16.0	12.1	13.0	9.0	12.6	14.6	5.1
5-9	89	11.1	3.5	8.0	14.8	32.9	15.7%	0.1	0.6	5.2	6.2	13.0	18.1	18.0	18.8	13.8	14.6	10.1	13.5	15.4	5.6
10-14	115	14.8	6.4	11.1	20.0	35.0	25.2%	0.1	0.6	6.9	8.1	14.0	25.3	25.3	26.2	16.7	16.6	11.0	16.9	19.6	9.2
Chest																					
<5	52	5.3	2.5	3.1	4.8	20.5	5.8%	0.3	11.4	8.4	10.2	7.8	6.1	6.9	2.3	0.7	0.7	0.7	0.4	0.5	3.3
5-9	37	7.5	2.6	3.9	10.5	26.1	8.1%	0.4	17.5	12.4	15.0	10.6	8.7	9.9	2.7	0.6	0.4	0.1	0.6	0.7	3.9
10-14	58	6.4	3.1	5.3	8.6	18.4	3.4%	0.3	13.6	10.3	13.2	9.9	8.0	8.9	2.2	0.2	0.1	0.1	0.1	0.1	3.6
Spine																					
<5	10	5.8	0.6	2.9	6.3	26.6	10.0%	0.8	10.8	8.4	7.7	8.3	7.5	8.6	3.6	1.0	0.7	0.1	1.2	1.8	4.4
5-9	14	7.7	1.5	4.1	10.5	26.7	14.3%	1.1	11.4	7.6	7.1	13.0	14.5	14.9	5.9	1.2	0.7	0.1	1.5	1.8	3.0
10-14	18	8.8	2.5	5.3	10.3	42.0	5.6%	0.7	6.4	8.5	9.7	9.7	17.9	20.3	4.7	0.7	0.4	0.2	0.2	0.2	3.9

N = Number

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Table 2

Lifetime attributable risk of solid cancer and leukemia from computed tomography (CT), per 10,000 CTs, and number of CTs leading to one cancer case, rounded to the nearest 10.

Age (years)	Head CT			Abdomen/Pelvis CT			Chest CT			Spine CT		
	Solid Cancer			Solid Cancer			Solid Cancer			Solid Cancer		
	Girls	Boys	Leukemia	Girls	Boys	Leukemia	Girls	Boys	Leukemia	Girls	Boys	Leukemia
Lifetime attributable risk of cancer per 10,000 CTs												
<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
Number of CTs leading to one cancer case (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

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Table 3

Projected number of future radiation-induced cancers [95% uncertainty limits (UL)] that could be related to the most commonly performed pediatric CTs in the US under three scenarios: (1) doses reflect those observed in clinical practice, (2) number of CTs reduced by one third, (3) doses above 75th percentile are lowered to median observed dose. Numbers of cancers are rounded to the nearest 10.

CT type	Estimated number of pediatric CTs in US (millions)	Projected number of future radiation-induced cancers related to pediatric CT use								
		Scenario 1: Doses reflect observed doses			*Scenario 2: Reduce number of exams by one third*			*Scenario 3: Doses above 75th percentile lowered to median*		
		Solid cancers	Leukemia cases	Total cancers (95% UL)	Solid cancers	Leukemia cases	Total cancers (95% UL)	Solid cancers	Leukemia cases	Total cancers (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)**