Radiation Exposure From Medical Imaging in Patients With Chronic and Recurrent Conditions

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Purpose: Advances in medical imaging have been associated with increased utilization and increased radiation exposure, especially for patients with chronic and recurrent conditions. The authors estimated the cumulative radiation doses from medical imaging for specific cohorts with chronic and recurrent conditions.

Methods: All patients diagnosed with hydrocephalus (n = 1,711), pulmonary thromboembolic disease (n = 3,220), renal colic (n = 5,855), and cardiac disease (n = 11,072) from January 1, 2000, to December 31, 2005, were retrospectively identified. Each imaging examination that used ionizing radiation from 2000 to 2008 was incorporated into an estimate of total effective dose and organ-specific doses. Patients with high levels of radiation exposure after 3 years (total effective dose > 50 mSv; dose to the ocular lens > 150 mSv) were identified.

Results: The mean estimated effective doses for the surviving diagnostic cohorts after 3 years were 12.3 mSv for patients with hydrocephalus, 21.7 mSv for those with pulmonary thromboembolic disease, 18.7 mSv for those with renal colic, and 14.0 mSv for those with cardiac disease. Among patients with hydrocephalus, 26.3% (339 of 1,291) had radiation doses > 150 mSv to the ocular lens within 3 years. In all cohorts, the proportion of patients with total effective doses > 50 mSv within 3 years was significantly higher for those diagnosed in 2004 and 2005 than for those diagnosed in 2000 and 2001.

Conclusion: Patients with hydrocephalus, pulmonary thromboembolic disease, renal colic, and cardiac disease received radiation exposures that may put them at increased risk for cancer. Moreover, the proportion who received estimated total effective doses > 50 mSv within 3 years was significantly higher for those diagnosed most recently. It is the responsibility of institutions and physicians to critically evaluate their infrastructures, diagnostic strategies, and imaging techniques for each individual patient, with an eye toward minimizing cumulative medical radiation exposure.

Key Words: Medical imaging, radiation safety, radiation exposure

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Recently, the National Council on Radiation Protection and Measurements [1] estimated that medical imaging is responsible for nearly half of the radiation exposure to the US population. Although the biologic effects from low-dose ionizing radiation remain controversial, x-rays represent a well-recognized carcinogen. Therefore, medical imaging with ionizing radiation should be kept to the minimum necessary for effective clinical care [2-5].

The ACR [6] recently recommended that hospitals and practices begin tracking patient radiation exposure. This is critical to justify the development and implementation of alternative strategies to reduce patient-specific radiation burden. Although lower dose and no-dose al-

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ternative imaging and clinical strategies are being developed, there are a variety of barriers to their adoption. Technical barriers include the high cost of new equipment and inadequate attention to radiation reduction techniques for existing equipment. Additionally, the high rate of obesity in the United States limits the utility of lower dose strategies because obese patients require higher dose techniques for diagnostic-quality imaging. Physicians also are reluctant not to image because of the confidence that imaging adds to clinical decision making.

Chronic and recurrent conditions require ongoing care and often result in repeat imaging and repeat exposure to ionizing radiation. We selected 4 cohorts of patients with different diagnoses: hydrocephalus, pulmonary thromboembolic disease, renal colic, and cardiac disease. These diagnoses often result in repeat imaging and have low-dose or no-dose alternative imaging techniques suitable for at least a subset of patients.

In this study, we examined institutional trends in radiation exposure over time for these 4 cohorts.

METHODS

The study was approved by our institutional review board, and informed consent was not required.

Radiation Dose Assignment

Using the estimates of Mettler et al [7], we assigned a total effective radiation dose for each examination performed at our institution in radiology, nuclear medicine, and invasive cardiology using mean and maximum values. We estimated absorbed organ doses to the breast, lung, thyroid, and bone marrow for CT using ImPACT CT Patient Dosimetry Calculator version 0.99× (ImPACT, London, UK), using the protocols programmed into each CT scanner. During the study and follow-up periods, helical CT technology was rapidly evolving, and scanners with 1, 4, 6, 16, and 64 detectors were all in regular use.

Radiation dose to the ocular lens from CT was estimated from the literature. We assigned mean ocular lens doses of 27 mSv for head CT and 56 mSv for orbit CT [8-12]. We also assigned organ doses for nuclear medicine imaging on the basis of published standards for our protocols [13]. For electrocardiographically gated cardiac CT, we used the absorbed and effective doses as calculated by Einstein et al [14].

For all of the examinations, CT with and without contrast was counted as two examinations, and the radiation dose was doubled. CT with contrast counted as a single examination, without allowing for the possibility of multiphase imaging.

Patient Selection

We retrospectively identified our study population cohorts using Clinical Looking Glass, an interactive software application developed at our institution to evaluate health care quality, effectiveness, and efficiency. The 4 cohorts were acquired from index encounters in our emergency department, inpatient, and outpatient services during the study period. *International Classification of Diseases, Ninth Revision* (ICD-9), codes (Table 1) were used to identify all patients diagnosed with hydrocephalus, pulmonary thromboembolic disease, renal colic, and cardiac disease between January 1, 2000, and June 30, 2005. This included all patients assigned to one of the above diagnostic categories regardless of whether they were imaged. Patients could enter each cohort only once. Medical records and the Social Security Death Index were searched to identify which patients died during follow-up. The follow-up period extended through December 31, 2008; hence, the entire study population had ≥3 years of follow-up.

Table 1. ICD-9 codes used to identify specific patient cohorts

Patient Cohort	ICD-9 Codes
Hydrocephalus	331.3, 331.4, 653.6, 653.61, 653.62, 653.63, 653.64, 741.0, 741.9, 742.3
PE/DVT	415.1, 415.11, 415.19, 451, 451.11, 451.2, 451.8, 451.81, 451.82, 451.83, 451.84, 451.89, 451.9, 453, 453.2, 453.40, 453.41, 453.42, 453.8, 453.9
Renal colic	788.0
Cardiac disease	410, 410.0, 410.00, 410.01, 410.02, 410.1, 410.10, 410.11, 410.12, 410.2, 410.20, 410.21, 410.22, 410.3, 410.30, 410.31, 410.32, 410.4, 410.40, 410.41, 410.42, 410.5, 410.50, 410.51, 410.52, 410.6, 410.60, 410.61, 410.62, 410.7, 410.70, 410.71, 410.72, 410.8, 410.80, 410.81, 410.82, 410.9, 410.90, 410.91, 410.92, 411, 411.0, 411.1, 411.8, 411.81, 411.89, 412, 413, 413.0, 413.1, 413.9, 414, 414.0, 414.00, 414.01, 414.02, 414.03, 414.04, 414.05, 414.06, 414.07, 414.1, 414.10, 414.11, 414.12, 414.19, 414.8, 414.9

Note: ICD-9 = *International Classification of Diseases, Ninth Revision*; PE/DVT = pulmonary thromboembolic disease.

Each patient's electronic medical record was surveyed to identify all medical imaging performed in radiology, nuclear medicine, and interventional cardiology (medical imaging). For CT, organ-specific absorbed dose estimations were made on the basis of specific scanner protocols.

We estimated absorbed organ doses to the breast, lung, thyroid, bone marrow, and ocular lens and the total effective dose for each patient. The effective dose is a derived quantity whose unit is the sievert, which weights the effects of nonuniform radiation exposure and results in a number intended to represent the equivalent stochastic biologic risks of uniform radiation exposure. We also estimated the effective dose for the surviving population in each cohort for the first year, the first 3 years, and for the subsets with 6 and 8 years of follow-up. Radiation dose is influenced by patient-specific and examination-specific factors, including patient size, age, and sex, as well as examination parameters, and is difficult to accurately estimate. When measured, actual patient radiation doses are often considerably higher than modeled estimates [6]. Our inner-city population has a very high obesity rate, requiring high-dose techniques to obtain diagnostic images. Additionally, our CT dose estimates did not account for multiphase scans, which are frequently performed in our institution. Hence, we performed radiation doses estimates for each cohort using mean and maximum dose values of Mettler et al [7] to better reflect the range of exposures to our population.

We used the annual occupational dose limits set by the National Council on Radiation Protection and Measurements of 50 mSv total effective dose and 150 mSv to the ocular lens to identify patients with high radiation exposure [15]. The Nuclear Regulatory Commission sets annual dose limits to the general public at 2% of the annual occupational dose limits. The rationale for these limits relates to the deleterious biologic effects of ionizing radiation, both stochastic and deterministic. Stochastic effects include carcinogenesis and hereditary defects; they can occur at any level of radiation exposure, but their probability of occurrence increases with increasing exposure. Deterministic effects include skin burns and cataracts and occur after a specific dose threshold has been reached. Although the threshold for detectable lens opacities for a single exposure has been estimated at 0.5 to 2.0 Sv and 5.0 Sv for cataracts, recent publications suggest that the threshold for cataracts may be ≤700 mSv [16,17]. Epidemiologic evidence, using the linear no-threshold model, suggests that the radiation dose from even one CT scan conveys a small increase in the lifetime attributable risk for cancer [18,19].

Statistical Methods

Chi-square tests were used to compare differences in proportions. A P value $< .05$ was considered significant.

RESULTS

The number of patients; the 1-year, 3-year, 6-year, and 8-year survival; and the sex and age for each cohort are summarized in Table 2. The estimated mean total effective and organ-specific doses from medical imaging to the survivors are detailed in Table 3. The percentage of sur-

Table 2. Cohort demographics for patients with hydrocephalus, PE/DVT, renal colic, and cardiac disease from 2000 to 2005

Variable	Hydrocephalus	Renal Colic	PE/DVT	Cardiac Disease
Female	867 (50.7%)	1,546 (48.0%)	3,611 (61.7%)	6,038 (54.5%)
Male	844 (49.3%)	1,674 (52.0%)	2,244 (38.3%)	5,034 (45.5%)
White	395 (23.1%)	650 (20.2%)	1,711 (29.2%)	3,341 (30.2%)
Black	534 (31.2%)	551 (17.1%)	2,086 (35.6%)	3,148 (28.4%)
Other	782 (45.7%)	2,019 (62.7%)	2,058 (35.1%)	4,583 (41.4%)
Age (y)	43.0 ± 31.9	43.4 ± 14.4	62.5 ± 19.6	65.9 ± 14.7
1-y survivor age (y)	41.6 ± 30.2	43.3 ± 14.2	65.1 ± 15.1	64.4 ± 14.3
3-y survivor age (y)	34.6 ± 30.1	43.1 ± 14.0	57.2 ± 19.8	63.1 ± 14.0
6-y survivor age (y)	27.2 ± 26.6	42.5 ± 14.1	55.4 ± 19.1	61.5 ± 13.6
8-y survivor age (y)	21.2 ± 22.5	42.3 ± 13.7	54.7 ± 19.2	59.8 ± 13.5
Alive at 1 y	1,416 (82.8%)	3,199 (99.3%)	4,294 (73.3%)	9,666 (87.3%)
Alive at 3 y	1,291 (75.5%)	3,154 (98.0%)	3,667 (62.6%)	8,656 (78.2%)
Alive at 6 y	686 (68.4%)	1,868 (96.3%)	1,579 (52.4%)	5,257 (67.5%)
Alive at 8 y	284 (69.6%)	630 (94.6%)	502 (46.1%)	1,917 (62.2%)
Number followed for 1 and 3 y	1,711	3,220	5,855	11,072
Number followed for 6 y	1,003	1,941	3,013	7,789
Number followed for 8 y	405	651	1,053	3,083

Note: Data are expressed as number (percentage) or as mean ± SD. PE/DVT = pulmonary thromboembolic disease.

Table 3. Radiation dose (mSv) to the surviving cohorts

Variable	Hydrocephalus	Renal Colic	PE/DVT	Cardiac Disease
1 y of follow-up	(n = 1,416)	(n = 3,199)	(n = 4,294)	(n = 9,666)
Total effective dose (mean)*	8.0 ± 14.4	12.6 ± 13.4	13.5 ± 25.5	7.5 ± 14.1
Total effective dose (maximum)†	17.2 ± 32.9	31.3 ± 35.	32.6 ± 63.2	24.0 ± 47.7
Breast dose	1.8 ± 7.1	1.4 ± 4.4	7.1 ± 18.1	3.0 ± 9.3
Lung dose	3.0 ± 9.3	4.1 ± 6.8	11.3 ± 24.2	4.5 ± 12.3
Thyroid dose	7.4 ± 18.8	1.3 ± 9.1	11.5 ± 30.8	4.4 ± 14.5
Bone marrow dose	8.0 ± 14.6	10.6 ± 12.2	10.4 ± 20.4	5.0 ± 10.9
Lens dose	86.0 ± 147.6	2.2 ± 14.3	19.0 ± 63.2	10.8 ± 33.8
3 y of follow-up	(n = 1,291)	(n = 3,154)	(n = 3,667)	(n = 8,656)
Total effective dose (mean)*	12.3 ± 22.0	18.7 ± 23.5	21.7 ± 38.7	14.0 ± 23.8
Total effective dose (maximum)†	27.1 ± 51.3	45.7 ± 61.2	51.2 ± 93.2	41.3 ± 72.0
Breast dose	3.1 ± 11.2	2.9 ± 10.4	10.7 ± 26.7	5.1 ± 14.4
Lung dose	5.1 ± 15.2	7.0 ± 15.1	17.2 ± 36.7	8.0 ± 19.5
Thyroid dose	11.6 ± 29.4	4.0 ± 22.4	18.7 ± 46.1	8.5 ± 24.5
Bone marrow dose	12.2 ± 21.6	15.5 ± 20.2	16.6 ± 30.8	9.5 ± 17.8
Lens dose	107.1 ± 170.5	5.0 ± 23.4	23.9 ± 74.4	13.9 ± 44.2
6 y of follow-up	(n = 686)	(n = 1,868)	(n = 1,579)	(n = 5,257)
Total effective dose (mean)*	15.9 ± 31.4	22.6 ± 35.7	27.1 ± 48.8	23.4 ± 35.9
Total effective dose (maximum)†	35.0 ± 72.1	54.2 ± 84.7	64.1 ± 118.3	63.1 ± 100.8
Breast dose	3.5 ± 14.8	4.3 ± 14.4	12.3 ± 31.8	8.4 ± 19.9
Lung dose	6.2 ± 20.6	9.2 ± 21.4	20.6 ± 44.1	13.4 ± 27.6
Thyroid dose	12.8 ± 33.8	7.0 ± 32.7	22.0 ± 52.6	16.1 ± 38.7
Bone marrow dose	15.2 ± 28.4	17.5 ± 28.6	20.6 ± 39.8	16.1 ± 27.1
Lens dose	110.7 ± 183.	7.7 ± 34.0	23.0 ± 67.0	16.9 ± 52.7
8 y of follow-up	(n = 284)	(n = 630)	(n = 502)	(n = 1,917)
Total effective dose (mean)*	15.1 ± 34.1	20.6 ± 44.7	25.5 ± 48.5	29.5 ± 48.1
Total effective dose (maximum)†	34.1 ± 76.4	48.5 ± 105.2	58.4 ± 119.9	71.7 ± 127.7
Breast dose	3.2 ± 21.6	5.3 ± 18.6	10.1 ± 24.6	10.3 ± 24.7
Lung dose	6.2 ± 30.7	10.0 ± 27.4	18.6 ± 37.3	17.1 ± 35.3
Thyroid dose	13.0 ± 47.7	10.6 ± 44.2	20.7 ± 49.7	23.5 ± 53.9
Bone marrow dose	14.9 ± 29.8	15.8 ± 35.7	18.6 ± 37.9	20.2 ± 34.7
Lens dose	109.9 ± 203.1	8.9 ± 45.1	17.7 ± 64.1	17.6 ± 63.2

Note: Data are expressed as mean ± SD. PE/DVT = pulmonary thromboembolic disease.
*Using the mean value for radiation exposure estimates in Mettler et al [7].
†Using the maximum value for radiation exposure estimates in Mettler et al [7].

vivors who had radiation dose estimates > 50 mSv total effective dose and 150 mSv to the ocular lens dose is described in Table 4.

For patients with hydrocephalus (n = 1,291), the mean total effective dose from medical imaging to surviving patients after 3 years using the mean and maximum dose estimates, respectively, was 12.3 and 27.1 mSv, and 84.1% of that exposure was from the radiology department and the remaining 15.9% from nuclear medicine and interventional cardiology. Using mean and maximum dose estimates, 5.6% (72 of 1,291) and 17.0% (220 of 1,291) of patients exceeded a total effective dose of 50 mSv, respectively. The maximum calculated lens dose was 1,654 mSv, and the highest total effective dose to an individual after 3 years was 610.4 mSv, using the maximum estimate. Compared with the 2000 and 2001 cohort, a significantly higher proportion of the 2004 and 2005 cohort exceeded a total effective dose of 50 mSv using the mean estimates (7.4% [24 of 326] vs 3.9% [21 of 540], $P < .0001$; Figure 1) and 150 mSv to the ocular lens within 3 years. This trend holds and the proportions are higher when the maximum estimates are used: 21.8% (71 of 326) vs 11.7% (63 of 540) ($P < .0001$).

Among patients with pulmonary thromboembolic disease (n = 3,668), the mean total effective dose using the mean and maximum dose estimates, respectively, was 21.7 and 51.2 mSv after 3 years, and 82.4% of that exposure was from the radiology department and the remaining 17.6% from nuclear medicine and interventional cardiology. Using mean and maximum dose estimates, 12.4% (456 of 3,668) and 28.3% (1,037 of 3,668) of patients exceeded a total effective dose of 50

Table 4. Proportion of the surviving cohort with radiation exposures > 50 mSv estimated effective dose and 150 mSv to the ocular lens

Variable	Hydrocephalus	Renal Colic	PE/DVT	Cardiac Disease
1 y of follow-up	(n = 1,416)	(n = 3,199)	(n = 4,294)	(n = 9,666)
>50 mSv total effective dose (mean)*	36 (2.5)	61 (1.9)	301 (7.0)	201 (2.1)
>50 mSv total effective dose (maximum)†	146 (10.3)	497 (15.5)	853 (19.9)	1,491 (15.4)
>150 mSv lens dose	289 (20.4)	0 (0.0)	13 (0.3)	2 (0.0)
3 y of follow-up	(n = 1,291)	(n = 3,154)	(n = 3,667)	(n = 8,656)
>50 mSv total effective dose (mean)*	72 (5.6)	213 (6.8)	456 (12.4)	533 (6.2)
>50 mSv total effective dose (maximum)†	220 (17.0)	831 (26.3)	1,037 (28.3)	2,232 (25.8)
>150 mSv lens dose	339 (26.3)	0 (0.0)	18 (0.5)	6 (0.1)
6 y of follow-up	(n = 686)	(n = 1,868)	(n = 1,579)	(n = 5,257)
>50 mSv total effective dose (mean)*	57 (8.3)	208 (11.1)	249 (15.8)	745 (14.2)
>50 mSv total effective dose (maximum)†	142 (20.7)	582 (31.2)	517 (32.7)	1,896 (36.1)
>150 mSv lens dose	178 (25.9)	2 (0.1)	5 (0.3)	9 (0.2)
8 y of follow-up	(n = 284)	(n = 630)	(n = 502)	(n = 1,917)
>50 mSv total effective dose (mean)*	22 (7.7)	68 (10.8)	80 (15.9)	383 (20.0)
>50 mSv total effective dose (maximum)†	54 (19.0)	162 (25.7)	139 (27.7)	711 (37.1)
>150 mSv lens dose	65 (22.9)	2 (0.3)	2 (0.4)	3 (0.2)

Note: Data are expressed as number (percentage). PE/DVT = pulmonary thromboembolic disease.
*Using the mean value for radiation exposure estimates in Mettler et al [7].
†Using the maximum value for radiation exposure estimates in Mettler et al [7].

mSv, respectively. The highest calculated breast dose was 327.8 mSv, and the highest total effective dose to an individual after 3 years was 984.8 mSv, using the maximum dose estimate. A higher proportion of the 2004 and 2005 cohort exceeded a total effective dose of 50 mSv within 3 years, using the mean estimates, compared with

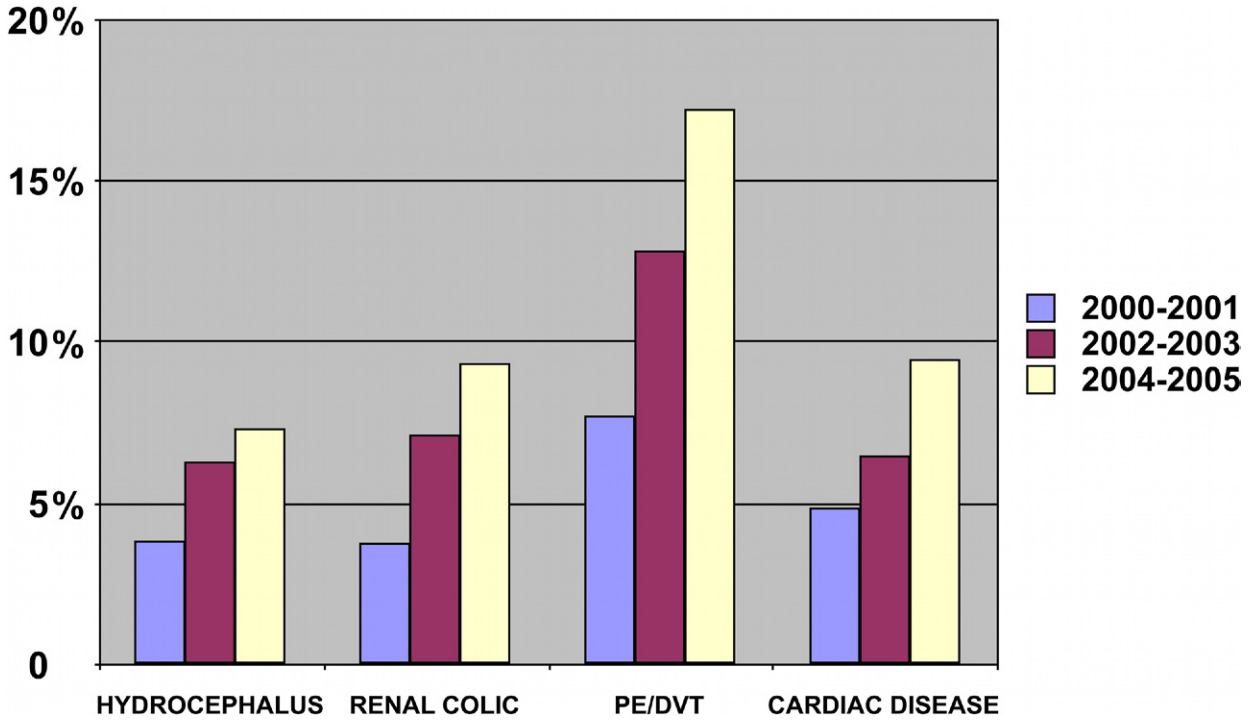

Fig 1. The proportion of surviving patients with hydrocephalus, renal colic, pulmonary thromboembolic disease (PE/DVT), and cardiac disease who exceeded 50 mSv in total effective dose over 3 years, using the mean estimates, increased for each cohort between 2000 and 2005.

the 2000 and 2001 cohort (17.3% [187 of 1,081] vs 7.8% [99 of 1,272], $P < .0001$). This trend holds and the proportions are higher when the maximum estimates are used: 33.4% (361 of 1,081) vs 21.7% (276 of 1,272) ($P < .0001$).

Among patients with renal colic (n = 3,154), the mean total effective dose after 3 years using the mean and maximum dose estimates, respectively, was 18.7 and 45.7 mSv, and 90.8% of that exposure was from the radiology department and the remaining 9.2% from nuclear medicine and interventional cardiology. Using mean and maximum dose estimates, 6.8% (213 of 3,154) and 26.3% (831 of 3,154) of patients exceeded 50 mSv in total effective dose, respectively. The highest total effective dose to an individual was 1,369.9 mSv after 3 years, using the maximum dose estimates. The proportion of patients exceeding 50 mSv in effective dose within 3 years, using the mean estimates, increased between the 2000 and 2001 cohort and the 2004 and 2005 cohort (3.8% [49 of 1,276] vs 9.4% [65 of 691], $P < .0001$). This trend holds and the proportions are higher when the maximum estimates are used: 19.9% (254 of 1,276) vs 32.6% (225 of 691) ($P < .0001$).

In patients with cardiac disease (n = 8,656), the mean total effective dose after 3 years using the mean and maximum dose estimates, respectively, was 14.0 and 41.3 mSv, and 63.5% of that exposure was from the radiology department and the remaining 36.5% from nuclear medicine and interventional cardiology. Using mean and maximum dose estimates, 6.2% (533 of 8,656) and 25.8% (2,232 of 8,656) of patients exceeded 50 mSv in total effective dose, respectively. The highest total effective dose for an individual after 3 years was 1,371.7 mSv, using maximum dose estimates. Once again, a significantly higher proportion of the 2004 and 2005 cohort (9.5% [123 of 1,291]) exceeded 50 mSv in total effective over 3 years compared with the 2000 and 2001 cohort (4.9% [214 of 4,355]) ($P < .0001$, χ^2) using the mean estimates. This trend holds and the proportions are higher when the maximum estimates are used: 35.1% (453 of 1,291) vs 21.2% (928 of 4,355) ($P < .0001$, χ^2).

When the 3-year radiation dose for each surviving cohort was evaluated by age, using the mean estimate (Figure 2), the proportion of patients who exceeded 50 mSv was generally higher with increasing age through the eighth decade. Patients with pulmonary thromboembolic disease consistently had the highest radiation exposures and the highest proportion who exceeded 50 mSv in every age group.

DISCUSSION

This study demonstrates that within 3 years, surviving patients with hydrocephalus, pulmonary thromboembolic disease, renal colic, or cardiac disease received estimated radiation doses that may put them at increased risk for cancer. A significantly higher proportion of patients from each cohort who were diagnosed in 2004 and 2005 had estimated radiation exposures > 50 mSv from med-

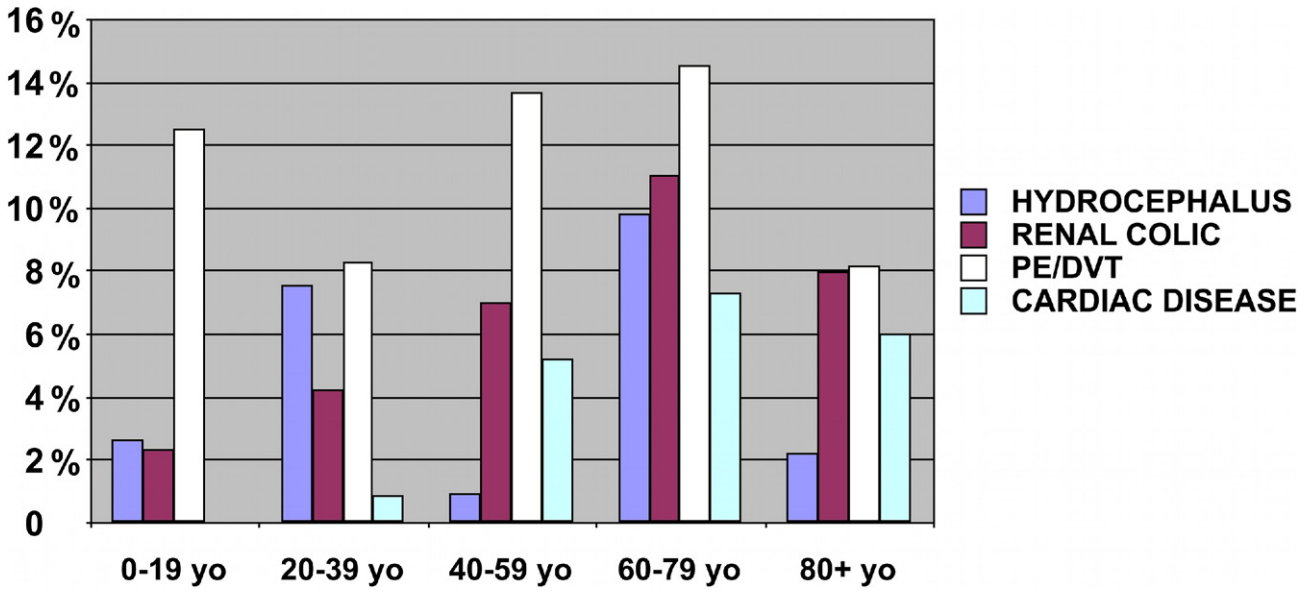

Fig 2. The proportion of patients who exceeded 50 mSv in total effective dose over 3 years, using the mean estimates, was generally higher with increasing age through the eighth decade. The proportion of patients with pulmonary thromboembolic disease who exceeded 50 mSv was consistently higher than for the other diagnostic cohorts, in each age group. PE/DVT = pulmonary thromboembolic disease.

ical imaging, compared with those diagnosed in 2000 and 2001. In patient care, radiation exposure is usually not monitored, and there is no consensus regarding dose limits. Rather, the physician caring for each patient is expected to evaluate the risk/benefit ratio. Fazel et al [20], in a series of nonelderly adults from 5 health care markets in the United States from 2005 to 2007, recently described >50 mSv as a very high patient radiation dose. Epidemiologic data suggest that these doses place patients at risk for both the stochastic (eg, cancer) and deterministic (eg, cataracts) effects of radiation exposure.

Although there is some disagreement about the level of risk from low-level radiation exposure over time, the current consensus favors the linear no-threshold model [4,5,21-23]. Under this model, the cumulative exposure to radiation over a lifetime is linearly associated with an increased risk for cancer. Brenner and Hall [18] estimated that as many as 2% of new cancers each year in the United States will be due to exposure to CT alone. Some contend that the model fails to account for the rate of radiation exposure (radiation flux) or for cells' capacity to repair radiation damage [4,5,21,22]. However, while recognizing these controversies, any added risk must be weighed against the benefits to patients, particularly when other options are available.

Whereas the risk for deterministic and stochastic effects from radiation exposure increases over a patient's lifetime and is not limited to any one year's exposure, we looked at as many follow-up data as were available to get a better idea of both the increasing exposure to the patient population and whether there were any identifiable trends toward increasing ionizing radiation exposure. We found that for all 4 cohorts, survivors demonstrated an increase in the mean total effective dose between the 3-year and 6-year follow-up period. This finding was more inconsistent among the surviving subset with 8 years of follow-up, perhaps because of higher mortality among the sicker, more frequently imaged patients.

In this study, all 4 cohorts showed major and significant increases (range, 90%-147%) in the proportion of patients who exceeded 50 mSv in total effective dose over 3 years for the 2004 and 2005 cohort compared with the 2000 and 2001 cohort, using the mean estimates. Because our cohorts were constructed by diagnostic category regardless of whether patients were imaged, this increase in exposure over time clearly reflects the recent trend of increasing imaging utilization and, if unchecked, portends very high exposures, with the associated concomitant risks [18,23].

The increase in radiation exposure over time documented in this series mirrors national trends. A recent report from the National Council on Radiation Protection and Measurements [1] described a 600% rise in the per capita effective dose from medical imaging in the United States, from 0.54 mSv in 1980 to 3.2 mSv in 2006. This increased exposure is to a large degree attributable to an increased utilization of CT and nuclear myocardial perfusion imaging [20,24]. In the present series, all 4 cohorts had a majority of their radiation exposure from procedures in radiology. This ranged from 82% to 91% for pulmonary thromboembolic disease, hydrocephalus, and renal colic. However, for the cohort with cardiac disease, radiology contributed a smaller majority of 64% of the cohort's radiation exposure, with nuclear medicine and interventional cardiology contributing a substantial minority.

Breast dose, especially in young patients, is a concern. Younger patients are more susceptible to radiation damage and, with a longer life expectancy, have more time for radiation-induced cancers to develop. Radiation-induced breast cancer related to fluoroscopic exposure was demonstrated among patients with tuberculosis who underwent repeated fluoroscopically guided pneumothorax therapy. At follow-up, patients exposed to fluoroscopy (estimated dose, 1,000 mSv) were 80% more likely to develop breast cancer than the unexposed population and showed a relationship between age of exposure and risk for cancer [25]. The average estimated breast dose among patients with pulmonary thromboembolic disease in this study was 10.7 mSv at 3 years, and the highest estimated breast dose to an individual was 327.8 mSv, equivalent to the radiation exposure of 55 mammograms [7].

In addition to the ocular lens and breast, we also report organ-specific doses to the thyroid, lung, and bone marrow. These organs are known to be sensitive to the deleterious effects of radiation, although there is a paucity of literature regarding the clinical significance of exposures in the range of medical imaging. The doses we report were calculated on the basis of the specific protocols and scanners used to image the cohorts and are not based on generic data.

A variety of strategies are necessary to reduce the rapid rise in imaging with ionizing radiation. Educating clinicians, radiologists, and technologists plays a critical role in their implementation. Sistrom et al [26] demonstrated a decline in the growth of outpatient imaging using an order entry and decision support system to guide the choice and appropriateness of imaging. As institutions begin to implement radiation reduction and exposure tracking programs [27], special attention should be paid to both individual patients and cohorts, such as those in this study, who are subject to repeated examinations and higher cumulative doses. Additionally, attention to dose-lowering techniques and technological innovations such as model-based iterative reconstruction, if used properly, can contribute to lowering patient radiation exposure [28]. However, the current economic downturn in the

United States will, at least in the short term, affect capital budgets and may reduce the ability of practices and institutions to purchase the new equipment that uses recently developed radiation reduction technologies.

Valid lower or no-dose diagnostic strategies have already been evaluated for the diagnostic cohorts of the present study, and it is important for radiologists and clinicians to become familiar with these approaches to dose reduction. For hydrocephalus, rapid MRI or low-dose head CT is an appropriate alternative to full-dose head CT, particularly in follow-up [29,30].

There has been an increase in overall imaging for suspected pulmonary embolism in the United States coincident with the advent of multidetector CT pulmonary angiography [31]. Much of this increased imaging may be unnecessary [32]. Recent reports have validated the use of clinical decision rules and the D-dimer assay to obviate imaging in some patients [33]. Furthermore, ventilation-perfusion scanning, a lower dose alternative, provides only 1/7 of the total radiation dose [7] and perhaps 1/40 of the breast dose [34]. We developed an imaging algorithm for patients with suspected pulmonary embolism in our emergency room that resulted in a 20% decrease in the estimated radiation exposure, without a significant change in mortality or recurrent pulmonary thromboembolic disease on follow-up [35].

For patients with renal colic, the imaging standard is noncontrast CT. High radiation doses occur in patients with recurrent symptoms. Low-dose abdominal CT and ultrasound on follow-up can markedly reduce radiation dose [36].

For cardiac disease, stress echocardiography represents a no-dose alternative to nuclear myocardial perfusion imaging and coronary CT angiography. The appropriate imaging algorithms and intervals between examinations remain undefined. Cardiac catheterization and percutaneous coronary intervention have a clear outcomes benefit for acute coronary syndromes. However, outside that setting, the benefits are less well-demonstrated [37].

The major limitation of this study was its retrospective nature and, thus, our estimation of radiation exposure. We did not have access to the actual radiation dose. Prospectively, the dose-length product or the kerma-area product has been validated as a measure of radiation exposure, and if these data were recorded in a searchable manner, they could be used to estimate the effective dose, although they do not account for the ages or sex of patients [38]. Another limitation of this study was that radiation exposure could be estimated only for imaging that occurred at our institution, likely resulting in an underestimation. This underestimation is exacerbated by the fact that in inner-city populations, such as ours, patients often receive care from more than one institution, resulting not only in a lack of coordination of care but perhaps also duplicate imaging.

In conclusion, the recent trend of increasing utilization of medical imaging with ionizing radiation is particularly relevant to patients with chronic and recurrent conditions. Patients with hydrocephalus, pulmonary thromboembolic disease, renal colic, and cardiac disease in this series received radiation exposures that may put them at increased risk for cancer. Moreover, the proportion of patients who received estimated total effective doses $>$ 50 mSv within 3 years was significantly higher for those diagnosed most recently. It is the responsibility of institutions to implement the necessary infrastructure and for physicians to critically evaluate the diagnostic strategy and imaging technique for each individual patient, with an eye toward minimizing medical radiation exposure.

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