ORIGINAL CONTRIBUTION

Use of Diagnostic Imaging Studies and Associated Radiation Exposure for Patients Enrolled in Large Integrated Health Care Systems, 1996-2010

Rebecca Smith-Bindman, MD

Diana L. Miglioretti, PhD

Eric Johnson, MS

Choonsik Lee, PhD

Heather Spencer Feigelson, PhD, MPH

Michael Flynn, PhD

Robert T. Greenlee, PhD, MPH

Randell L. Kruger, PhD

Mark C. Hornbrook, PhD

Douglas Roblin, PhD

Leif I. Solberg, MD

Nicholas Vanneman, MA

Sheila Weinmann, PhD

Andrew E. Williams, PhD

THE USE OF DIAGNOSTIC IMAGING in the Medicare population has increased significantly over the last 2 decades, particularly using expensive new technologies such as computed tomography (CT), magnetic resonance imaging (MRI), and nuclear medicine positron emission tomography (PET).[1,2] The development and improvement in these advanced diagnostic imaging technologies is widely credited with leading to earlier and more accurate diagnoses of disease using noninvasive techniques. However, utilization and costs of advanced diagnostic imaging in the United States

For editorial comment see p 2434.

Author Video Interview available at www.jama.com.

Context Use of diagnostic imaging has increased significantly within fee-for-service models of care. Little is known about patterns of imaging among members of integrated health care systems.

Objective To estimate trends in imaging utilization and associated radiation exposure among members of integrated health care systems.

Design, Setting, and Participants Retrospective analysis of electronic records of members of 6 large integrated health systems from different regions of the United States. Review of medical records allowed direct estimation of radiation exposure from selected tests. Between 1 million and 2 million member-patients were included each year from 1996 to 2010.

Main Outcome Measure Advanced diagnostic imaging rates and cumulative annual radiation exposure from medical imaging.

Results During the 15-year study period, enrollees underwent a total of 30.9 million imaging examinations (25.8 million person-years), reflecting 1.18 tests (95% CI, 1.17-1.19) per person per year, of which 35% were for advanced diagnostic imaging (computed tomography [CT], magnetic resonance imaging [MRI], nuclear medicine, and ultrasound). Use of advanced diagnostic imaging increased from 1996 to 2010; CT examinations increased from 52 per 1000 enrollees in 1996 to 149 per 1000 in 2010, 7.8% annual increase (95% CI, 5.8%-9.8%); MRI use increased from 17 to 65 per 1000 enrollees, 10% annual growth (95% CI, 3.3%-16.5%); and ultrasound rates increased from 134 to 230 per 1000 enrollees, 3.9% annual growth (95% CI, 3.0%-4.9%). Although nuclear medicine use decreased from 32 to 21 per 1000 enrollees, 3% annual decline (95% CI, 7.7% decline to 1.3% increase), PET imaging rates increased after 2004 from 0.24 to 3.6 per 1000 enrollees, 57% annual growth. Although imaging use increased within all health systems, the adoption of different modalities for anatomic area assessment varied. Increased use of CT between 1996 and 2010 resulted in increased radiation exposure for enrollees, with a doubling in the mean per capita effective dose (1.2 mSv vs 2.3 mSv) and the proportion of enrollees who received high (>20-50 mSv) exposure (1.2% vs 2.5%) and very high (>50 mSv) annual radiation exposure (0.6% vs 1.4%). By 2010, 6.8% of enrollees who underwent imaging received high annual radiation exposure (>20-50 mSv) and 3.9% received very high annual exposure (>50 mSv).

Conclusion Within integrated health care systems, there was a large increase in the rate of advanced diagnostic imaging and associated radiation exposure between 1996 and 2010.

JAMA. 2012;307(22):2400-2409   www.jama.com

are high and rapidly growing,[3,4] and payments to physicians for diagnostic imaging have had the highest rate of growth among all physician services

Author Affiliations are listed at the end of this article.

Corresponding Author: Rebecca Smith-Bindman, MD, Department of Radiology and Biomedical Imaging, 350 Parnassus Ave, Ste 307, University of California, San Francisco, CA 94143-0336 (rebecca.smith-bindman@ucsf.edu).

over the last decade.[3,4] Computed tomography and nuclear medicine examinations deliver much higher doses of ionizing radiation than conventional radiographs, and extensive epidemiological evidence has linked exposure to radiation levels in this range with the development of radiation-induced cancers.[5,6] It is estimated that 2% of future cancers will result from current imaging use, if imaging continues at current rates.[7,8]

Most studies that have evaluated patterns of diagnostic imaging have assessed insurance claims for fee-for-service insured populations[1,9-11] where financial incentives encourage imaging.[12,13] No large, multisite studies have assessed imaging trends in integrated health care delivery systems that are clinically and fiscally accountable for the outcomes and health status of the population served.[13,14] Understanding imaging utilization and associated radiation exposure in these settings could help us determine how much of the increase in imaging may be independent of direct financial incentives.

We conducted a population-based study of diagnostic imaging trends between 1996 and 2010 among members of 6 geographically diverse integrated health care delivery systems that have both care delivery and insurance relationships with their member-patients. The availability of administrative and electronic medical record data on all health care received—including diagnostic imaging—allowed us to assess patterns of imaging over time as they varied by health system and patient demographics.

METHODS

The study population includes members enrolled in 1 of 6 health care systems, each of which participates in the HMO Research Network,[15] including Group Health Cooperative in Washington State; Kaiser Permanente in Colorado, Georgia, Hawaii, Oregon, and Washington; and Marshfield Clinic and Security Health Plan in Wisconsin. We included all members enrolled in group-

and staff-model plans, and in addition to commercial plans, the health system members included enrollees with prepaid Medicaid contracts, state-subsidized prepaid plans, and Medicare Advantage plans. We excluded data for health plan members who purchased fee-for-service (network) plans and patients treated at health plan facilities without being enrolled in the health maintenance organization (HMO) plans because of the high likelihood of incomplete capture of imaging data for these patients. Enrollees were included in the study for each year in which they were continuously enrolled. A data resource utility called the Virtual Data Warehouse that includes comprehensive diagnostic imaging data was used to capture standardized data from the electronic medical and administrative records.[16]

A waiver of informed consent was received for each participating health care system. The study was approved by the institutional review board of every health plan included as well as the University of California, San Francisco.

Imaging Utilization

All diagnostic imaging tests were included regardless of where they were ordered, performed, or interpreted. Imaging procedures done in conjunction with radiation treatment for cancer were not included. Individual health systems contributed data for at least 11 years and up to 15 years, depending on participation in their local Virtual Data Warehouse. Imaging procedures were coded using standardized codes from the *International Classification of Diseases, Ninth Revision, Clinical Modification*; *Current Procedural Terminology, Fourth Edition*; and Healthcare Common Procedure Coding System.[17]

There were 1467 unique imaging codes across all years, and each was mapped to an anatomic area (ie, abdomen/pelvis [abdomen], brain [central nervous system, abbreviated as CNS], breast, cardiovascular, chest, extremity, obstetric, spine, and other/unknown). Imaging codes for extremity and spine that could not be

differentiated were combined as musculoskeletal. Examinations were also characterized by modality (ie, angiography/fluoroscopy, CT, MRI, nuclear medicine [PET, a subset of nuclear medicine categorized separately because of its high cost], radiography, ultrasound, and other/unknown[17]). Multiple examinations with the same procedure code performed on the same patient on the same day were counted only once to reduce the likelihood of overcounting.

Radiation Dose

Of the 1467 imaging codes, 1068 were associated with the delivery of ionizing radiation, including angiography/fluoroscopy, CT, nuclear medicine, and radiography. Ultrasound and MRI do not use ionizing radiation and thus were not included. Because CT and nuclear medicine examinations contribute such a large proportion of the radiation exposure from imaging, we newly abstracted additional patient-level data to allow accurate estimation of dose. For CT, we randomly selected patients based on age and sex in each year from across the participating sites who underwent the most frequent CT examination types (n=4188 examinations) and abstracted the primary determinants of dose from each examination (ie, body region imaged, scan length, kilovolt peak [kVp], milliampere [mA] or mA seconds [mAs], rotation time, pitch, and CT manufacturer and model). These technical parameters were abstracted using automated computer programs that extracted these data from the Digital Imaging and Communications in Medicine (DICOM) tags stored in the Picture Archiving and Communications System (PACS). For examinations prior to when each health plan adopted PACS, these parameters were manually abstracted from the stored or printed CT images.

Using these parameters, we estimated the effective dose for each CT examination. Effective dose is a metric that takes into account both the amount of radiation to which a person is exposed and the biological effect of that

radiation on the exposed organs. It is defined as a dose equivalent to the dose (and subsequent harm) that would have been received had the full body been irradiated by a single source. Thus, a large dose to a single organ might have a similar effective dose, and thus estimated to have a similar future cancer risk, as a smaller dose to the entire body. In general, effective dose is estimated as a weighted average of organ doses, with weights corresponding to the sensitivity of each organ to developing cancer after radiation exposure. We used a new method for estimating organ-specific dose based on improved sex- and age-specific phantom anatomy using mathematical hybrid phantoms.[18,19] Organ-equivalent doses were weighted to generate effective dose by the tissue weighting factors provided in the International Commission on Radiological Protection publication 103.[20]

For nuclear medicine examinations, effective dose varies by the administered radiopharmaceutical and activity. At a single facility, we collected data on the type and injected volume of radiopharmaceutical for a consecutive sample of 5502 nuclear medicine examinations. Using these data and standard calculations for estimating effective dose for each examination with methods described by the Medical Internal Radiation Dose committee,[21] we estimated the dose for each examination type. For mammography, we obtained unpublished patient-level data from the American College of Radiology Imaging Network Digital Mammography Imaging Screening Trial to estimate dose and variation in dose.[22] For the remaining imaging study types (ie, less common CT types, fluoroscopy, angiography/fluoroscopy, and radiography), we completed a detailed review of the published literature to estimate dose and measure of variability in dose for each study.

The dosage data provided detailed information on the variability in effective radiation dose within procedure type. We used this information to create a dose estimate that accounts for the variability of dose. A truncated log-

normal distribution was a good fit to dose data, with the truncation occurring at 3 SDs on the log scale. For each examination each patient underwent during the study period, we randomly imputed a dose value from the log-normal distribution. This technique allowed each person to be assigned a dose value that reflected the true underlying distribution in dose, rather than assuming each person received the mean dose associated with a particular examination type.

We used the data describing the number of imaging tests and associated radiation dose per test to calculate the total dose of radiation each member received each year of the study and to calculate the collective effective dose to the entire population. To estimate cumulative annual radiation exposure for each patient, we summed the doses for each examination within each year. If patients underwent more than 1 examination using the same modality on the same anatomic area on the same day, we only included the examination with the highest radiation exposure to calculate dose so as not to overestimate doses received.

Statistical Analysis

We calculated the number of imaging examinations per 1000 enrollees per year (rates) by modality, anatomic area, and health system (overall and stratified by site and age). The calculations of rates over time were adjusted for site, age, and sex. This standardization was performed in Stata (StataCorp) by fitting log-linear regression models with Gaussian errors, including site, age, sex, and year as covariates. Based on the fitted model, we estimated average rates using marginal standardization, treating each site with equal weight and adjusting to the observed age and sex distribution.[23]

For modality-specific analyses, we calculated the per capita dose in mSv per person per year by dividing the collective effective dose by the number of individuals (whether exposed to radiation from diagnostic imaging or not). For analyses that ignored modality, we

estimated the individual radiation dose per year and calculated descriptive statistics in annual radiation exposure, including the percentage of enrollees who underwent a high annual radiation exposure (defined as 20-50 mSv)[11,20] or a very high radiation exposure (>50 mSv).[11,20] We calculated the relative contribution (mean dose and percentage of dose) from the different imaging modalities over time. When showing imaging rates (TABLE 1), we show data from 2008, the most recent year where all sites contributed data.

We used SAS version 9.2 (SAS Institute) and Stata versions 11.1 and 12.0 for statistical analysis. All statistical tests were 2-sided and significance was set at $P < .05$.

RESULTS

Between 933 897 and 1 998 650 enrollees were included during each year of the study. The age distribution of health plan members roughly paralleled that of the states in which the members were enrolled, and 52.5% of enrollees were female (see the eTable, available at http://www.jama.com). Enrollees underwent a total of 30.9 million imaging examinations during the 15-year study (25.8 million person-years), reflecting an average of 1.18 tests per person per year (95% CI, 1.17-1.19), of which 35% were advanced diagnostic imaging (ie, CT, MRI, nuclear medicine, and ultrasound).

The rates of imaging examinations per 1000 enrollees in 2008 by modality, site, and anatomic area are provided in Table 1. The total rate of imaging was 1420 examinations per 1000 enrollees per year—the most common being radiography (783/1000, 55.1% of all examinations), followed by ultrasound (271/1000, 19.1%), CT (177/1000, 12.5%), MRI (72/1000, 5.1%), angiography/fluoroscopy (64/1000, 4.5%), and nuclear medicine (53/1000, 3.7%).

Although the percentage of examinations for each modality was relatively similar across health systems (51.8%-57.6% of examinations involved radiography across sites and 10.8%-13.9% of examinations used CT

across sites), there were significant differences across health systems in the rates of imaging for each examination type. For example, the utilization of MRI ranged from 55 to 88 examinations per 1000 enrollees (relative risk [RR] between highest and lowest site, 1.6; $P < .001$). Angiography/fluoroscopy utilization varied the most across sites (RR, 4.4; $P < .001$) and radiography had the least variation in use across sites (RR, 1.3; $P < .001$).

Utilization Over Time

Radiography and angiography/fluoroscopy rates were relatively stable over time: radiography increased 1.2% per year, and angiography/fluoroscopy decreased 1.3% per year. In contrast, the utilization of advanced diagnostic imaging changed markedly (**FIGURE 1**). Computed tomography examinations tripled (52/1000 enrollees in 1996 to 149/1000 in 2010, 7.8% annual growth; 95% CI, 5.8%-9.8%); MRIs

quadrupled (17/1000 to 65/1000, 10% annual growth; 95% CI, 3.3%-16.5%); ultrasounds approximately doubled over the same period (134/1000 to 230/1000, 3.9% annual growth; 95% CI, 3.0%-4.9%). Nuclear medicine rates decreased (32/1000 to 21/1000, 3% annual decline; 95% CI, 7.7% decline to 1.3% increase), although after 2004, PET imaging rates increased from 0.24 per 1000 enrollees to 3.6 per 1000 enrollees, 57% annual growth.

Table 1. Examinations per 1000 Enrollees per Year by Modality, Anatomic Area, and Health System, 2008[a]

	No. (%)						
	Average	A	B	C	D	E	F
Angiography/fluoroscopy	64 (4.5)	66 (4.1)	62 (4.6)	23 (1.9)	103 (6.1)	54 (3.8)	73 (5.8)
Abdomen	14 (1.0)	14 (0.9)	16 (1.2)	11 (0.9)	18 (1.0)	14 (1.0)	10 (0.8)
Cardiovascular	43 (3.1)	48 (3.0)	35 (2.6)	7 (0.6)	79 (4.7)	33 (2.3)	58 (4.7)
Other	7 (0.5)	4 (0.3)	12 (0.9)	5 (0.4)	6 (0.4)	7 (0.5)	5 (0.4)
CT	177 (12.5)	195 (12.3)	176 (13.0)	160 (13.1)	199 (11.8)	200 (13.9)	136 (10.8)
Abdomen	89 (6.3)	97 (6.1)	87 (6.4)	84 (6.9)	94 (5.6)	100 (7.0)	71 (5.6)
Cardiovascular	9 (0.6)	9 (0.6)	11 (0.8)	1 (0.1)	11 (0.6)	16 (1.1)	5 (0.4)
Chest	23 (1.6)	26 (1.6)	21 (1.6)	20 (1.6)	27 (1.6)	24 (1.7)	23 (1.8)
CNS	43 (3.0)	45 (2.9)	43 (3.2)	45 (3.7)	54 (3.2)	45 (3.1)	27 (2.2)
Spine	6 (0.5)	7 (0.5)	8 (0.6)	4 (0.4)	6 (0.3)	8 (0.6)	5 (0.4)
Other	6 (0.5)	10 (0.6)	6 (0.4)	5 (0.4)	8 (0.5)	6 (0.4)	4 (0.3)
MRI	72 (5.1)	88 (5.6)	73 (5.4)	60 (4.9)	80 (4.7)	75 (5.3)	55 (4.3)
Cardiovascular	5 (0.4)	7 (0.4)	5 (0.3)	6 (0.5)	9 (0.6)	3 (0.2)	2 (0.2)
CNS	18 (1.3)	23 (1.4)	18 (1.3)	15 (1.2)	21 (1.3)	23 (1.6)	11 (0.9)
Extremity	19 (1.3)	26 (1.7)	16 (1.2)	16 (1.3)	18 (1.0)	19 (1.3)	18 (1.4)
Spine	23 (1.6)	27 (1.7)	23 (1.7)	19 (1.6)	24 (1.4)	26 (1.8)	17 (1.4)
Other	7 (0.5)	5 (0.3)	11 (0.8)	5 (0.4)	8 (0.5)	5 (0.3)	6 (0.5)
Nuclear medicine	53 (3.7)	60 (3.8)	31 (2.3)	49 (4.0)	85 (5.0)	45 (3.1)	50 (4.0)
Cardiovascular	41 (2.9)	45 (2.8)	16 (1.2)	41 (3.3)	70 (4.1)	34 (2.3)	40 (3.2)
Chest	2 (0.1)	1 (0.1)	1 (0.1)	1 (0.1)	3 (0.2)	2 (0.1)	1 (0.1)
Musculoskeletal	5 (0.4)	7 (0.5)	6 (0.5)	4 (0.3)	5 (0.3)	4 (0.3)	6 (0.5)
Other	6 (0.4)	7 (0.4)	8 (0.6)	4 (0.3)	6 (0.4)	5 (0.4)	4 (0.3)
Radiographs	783 (55.1)	866 (54.7)	771 (57.0)	682 (56.0)	870 (51.8)	826 (57.6)	681 (54.3)
Abdomen	28 (2.0)	32 (2.0)	27 (2.0)	22 (1.8)	37 (2.2)	25 (1.7)	24 (1.9)
Breast[b]	330 (23.2)	375 (23.7)	317 (23.5)	278 (22.9)	371 (22.1)	351 (24.5)	287 (22.9)
Chest	195 (13.7)	197 (12.5)	196 (14.5)	207 (17.0)	220 (13.1)	185 (12.9)	164 (13.0)
Musculoskeletal	357 (25.2)	406 (25.6)	356 (26.4)	290 (23.8)	379 (22.6)	407 (28.4)	305 (24.3)
Other	26 (1.9)	30 (1.9)	22 (1.6)	14 (1.2)	36 (2.1)	21 (1.5)	34 (2.7)
Ultrasound	271 (19.1)	308 (19.5)	238 (17.6)	244 (20.0)	344 (20.5)	235 (16.4)	260 (20.7)
Abdomen	80 (5.7)	87 (5.5)	90 (6.7)	67 (5.5)	81 (4.8)	96 (6.7)	60 (4.8)
Breast[b]	33 (2.3)	34 (2.2)	23 (1.7)	35 (2.9)	50 (3.0)	27 (1.9)	26 (2.1)
Cardiovascular	111 (7.8)	128 (8.1)	73 (5.4)	107 (8.8)	168 (10.0)	63 (4.4)	127 (10.1)
Obstetric[b]	71 (5.0)	80 (5.1)	81 (6.0)	58 (4.7)	83 (4.9)	82 (5.7)	46 (3.6)
Other	24 (1.7)	31 (2.0)	20 (1.5)	20 (1.7)	23 (1.4)	17 (1.2)	35 (2.8)
Total	1420 (100)	1582 (100)	1351 (100)	1218 (100)	1680 (100)	1435 (100)	1254 (100)

Abbreviations: CNS, central nervous system; CT, computed tomography; MRI, magnetic resonance imaging.
[a] All rates adjusted to a standardized age and sex distribution. Each lettered column represents 1 health plan, and within each column, the percentages sum to 100%. 2008 was the most recent year for which each health plan was included.
[b] Breast and obstetrical rates calculated among women.

The increase in advanced diagnostic imaging with both age and year is shown in **FIGURE 2**. Diagnostic imaging increased with age, and within each age group, advanced diagnostic imaging rates increased rapidly for many years and then flattened or minimally declined in the more recent years. For CT, growth in imaging tended to flatten around 2007. For MRI, rates peaked around 2007, with slight declines in subsequent years. For nuclear medicine, a marked reduction in imaging rates occurred from 2006 onward; however, PET imaging rates increased steadily through 2010.

Radiation Exposure and Changes Over Time

The increase in the utilization of CT resulted in an increase in enrollee exposure to radiation, with the mean per capita effective dose rising from 1.2 mSv in 1996 to 2.3 mSv in 2010. The percent of enrollees who received high (>20-50 mSv) or very high (>50 mSv) radiation exposure during a given year also approximately doubled across study years. By 2010, 2.5% of enrollees received a high annual dose of greater than 20 to 50 mSv, and 1.4% received a very high annual dose of greater than 50 mSv (**TABLE 2**).

The average effective dose to those individuals who were exposed to any radiation from medical imaging increased from approximately 4.8 mSv in 1996 to 7.8 in 2010 (3.2% annual growth; 95% CI, 3.1%-3.3%). By 2010, 6.8% of patients who underwent imaging received a high dose of more than 20 to 50 mSv and 3.9% of patients received a very high dose above 50 mSv during this single year. The distribution in dose over time is shown in **FIGURE 3**. There was a gradual increase in the radiation dose received by individuals in the top 1% and 10% of those exposed. By 2010, the highest 1% of exposed individuals received around 100 mSv, and the highest 10% of exposed individuals received around 20 mSv.

The increase in CT use accounted for the increase in the number of enrollees exposed to high (>20-50 mSv) and very high (>50 mSv) radiation exposures. In 1996, CT accounted for 5.7% of examinations and 30.3% of enrollees' exposure to ionizing radiation while contributing to a per capita exposure of 0.38 mSv per enrollee (**TABLE 3**). By 2010, CT accounted for 12.0% of examinations and 67.8% of radiation exposure and contributed 1.58 mSv per enrollee (a 4-fold increase in per capita radiation exposure from CT). Angiog-

Figure 1. Imaging Examinations by Modality and Year, Adjusted to a Standard Age Distribution Across Sites and Years
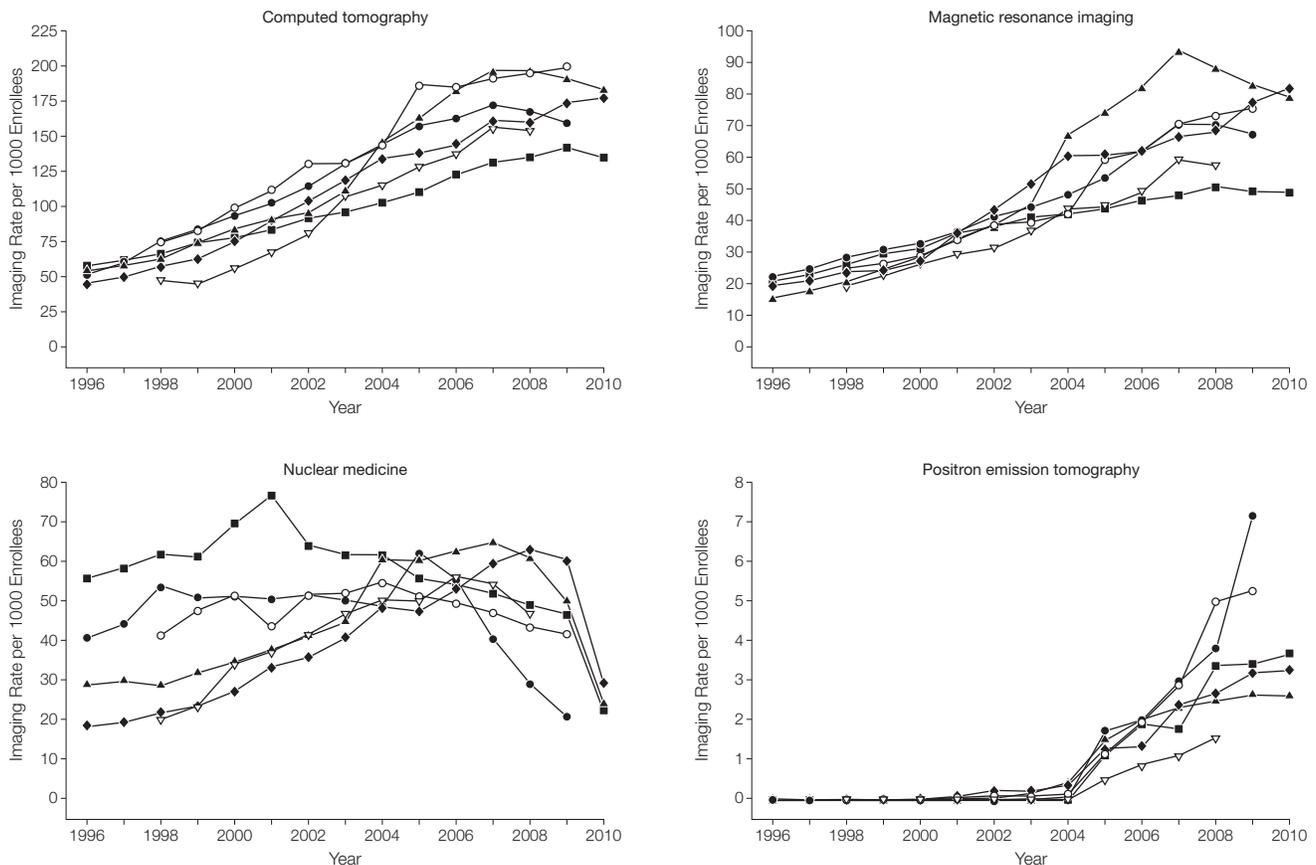
Each line represents a single health plan. All rates are adjusted to a standardized age and sex distribution.

raphy/fluoroscopy accounted for a declining proportion of examinations (reduced from 7.4% to 4.6%) and a reduced contribution to absolute radiation exposure (reduced from 0.52 to 0.34 mSv per year), reflecting a reduction from 42.3% to 14.6% of enrollees' total radiation exposure.

COMMENT

We found the increase in imaging studies among 6 large integrated HMOs was substantial over the last 15 years, par-

Figure 2. Imaging Examinations by Modality, Age, and Year (1996-2010)
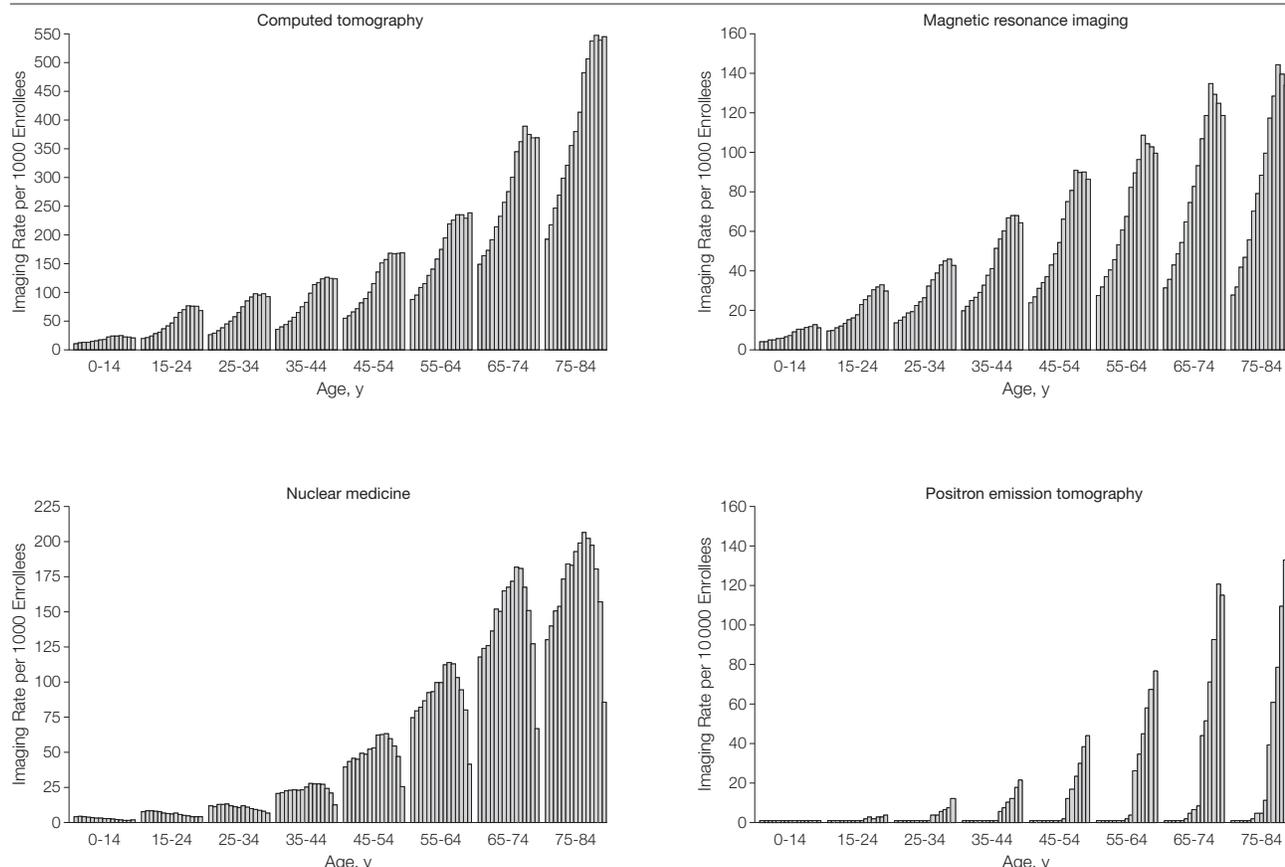
All results adjusted to a standard age distribution. Each cluster of bars represents changing rates of imaging over time within age strata; each bar represents a year from 1996 through 2010 consecutively. The median SE was 4.7/1000 enrollees for CT (IQR, 4.1-6.0); 2.2/1000 for MRI (IQR, 1.9-2.8); 4.1/1000 for nuclear medicine (IQR, 3.5-5.2); and 2.9/1000 for PET (IQR, 2.6-3.7).

Table 2. Exposure to Ionizing Radiation by Age and Level of Exposure During 1996 and 2010

		All Enrollees, No. (%)					Enrollees Who Underwent Imaging, No. (%)		
Age, y	No.	None	Low (>0-3 mSv/y)	Moderate (>3-20 mSv/y)	High (>20-50 mSv/y)	Very High (>50 mSv/y)	Moderate (>3-20 mSv/y)	High (>20-50 mSv/y)	Very High (>50 mSv/y)
During 1996									
0-14	230 181	195 542 (85.0)	32 076 (13.9)	2224 (1.0)	265 (0.1)	72 (0.0)	2224 (6.4)	265 (0.8)	72 (0.2)
15-44	466 078	367 852 (78.9)	81 836 (17.6)	12 626 (2.7)	2775 (0.6)	988 (0.2)	12 626 (12.9)	2775 (2.8)	988 (1.0)
45-64	267 162	160 025 (59.9)	86 289 (32.3)	14 189 (5.3)	4405 (1.6)	2255 (0.8)	14 189 (13.2)	4405 (4.1)	2255 (2.1)
≥65	129 712	58 164 (44.8)	49 192 (37.9)	14 120 (10.9)	5140 (4.0)	3095 (2.4)	14 120 (19.7)	5140 (7.2)	3095 (4.3)
All	1 093 133	781 583 (71.5)	249 393 (22.8)	43 159 (3.9)	12 585 (1.2)	6410 (0.6)	43 159 (13.9)	2585 (4.0)	6410 (2.1)
During 2010									
0-14	152 419	125 169 (82.1)	24 878 (16.3)	1908 (1.3)	358 (0.2)	106 (0.1)	1908 (7.0)	358 (1.3)	106 (0.4)
15-44	350 268	263 377 (75.2)	69 278 (19.8)	12 063 (3.4)	4014 (1.1)	1538 (0.4)	12 063 (13.9)	4014 (4.6)	1538 (1.8)
45-64	303 414	159 381 (52.5)	107 357 (35.4)	20 974 (6.9)	9955 (3.3)	5748 (1.9)	20 974 (14.6)	9955 (6.9)	5748 (4.0)
≥65	127 796	47 825 (37.4)	48 892 (38.3)	16 432 (12.9)	8822 (6.9)	5824 (4.6)	16 432 (20.5)	8822 (11.0)	5824 (7.3)
All	933 897	595 752 (63.8)	250 405 (26.8)	51 377 (5.5)	23 149 (2.5)	13 216 (1.4)	51 377 (15.2)	23 149 (6.8)	13 216 (3.9)

alleling the increase reported among fee-for-service insured populations. For example, among the HMO enrollees 65 years and older, rates of imaging with CT increased an average of 10.2% annually between 1998 and 2005, and slowed to 4.2% annual growth from 2005 to 2008, similar to the respective 10.1% and 5.1% growth rates recently reported among Medicare fee-for-service beneficiaries during the same time periods.[2,24] Use of MRI also increased rapidly among the HMO enrollees, with 14.5% and 6.5% average annual increase in these 2 periods—similar to that reported for Medicare fee-for-service beneficiaries (13.5% and 2.2%, respectively).[2]

The increase in imaging use over this period was likely driven by many factors, including improvements in the technology that have led to expansion of clinical applications, patient- and physician-generated demand, defensive medical practices,[25] and medical uncertainty[26,27]—all factors that would be expected to influence utilization across all systems of medical care. However, strategies that have been adopted by most private commercial payers to control imaging costs, such as use of radiology benefit management firms that require preapproval or prenotification[28,29] and member copayments, have not been widely adopted within these settings. Only 2 of these health plans have recently adopted copayments for advanced imaging (one at $10 and one at $50). Although several plans have recently adopted decision sup-port software, it is too early to assess whether greater adherence to appropriateness criteria included with the software products may influence utilization rates.

Although the increase in imaging studies was similar between HMO members and Medicare fee-for-service insured beneficiaries, the rates of imaging seem to be modestly lower among HMO enrollees. For example, in 2006, HMO enrollees 65 years and older underwent 474 CTs and 123 MRIs per 1000 enrollees, whereas Medicare fee-for-service enrolled adults underwent 550 CTs and 192 MRIs, 15% and 35% lower rates, respectively.[2] While some of this difference may be due to underlying geographic variation in imaging rates (we included 6 HMOs

Figure 3. Annual Average Effective Dose Received by Enrollees by Health Plan and Year
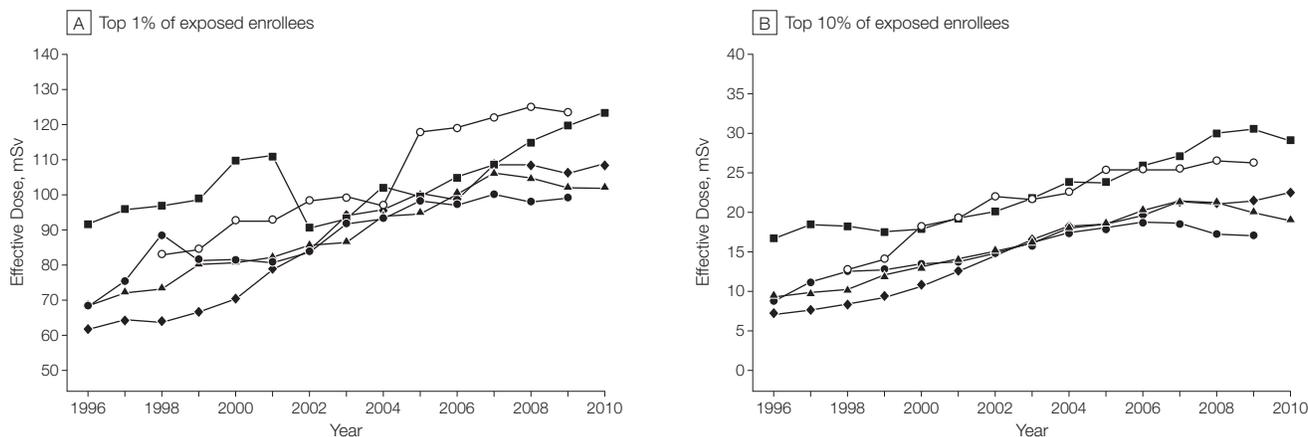
A, Highest 1% of exposed enrollees. B, Highest 10% of exposed enrollees. We calculated the average effective dose received by the highest 1% and 10% of health plan members across 5 sites, and the 95% CI had a width less than 2 mSv for A and less than 0.1 mSv for B. One health plan was unable to contribute data to either graph.

Table 3. Association of Different Modalities With Examination Rates and Annual Radiation Exposure

	Examinations per 1000 Enrollees, No. (%)			Average per Capita Radiation Dose by Modality, mSv (%)		
	1996	2003	2010	1996	2003	2010
Angiography/fluoroscopy	68 (7.4)	64 (5.8)	57 (4.6)	0.52 (42.3)	0.49 (26.5)	0.34 (14.6)
Computed tomography	52 (5.7)	108 (9.7)	149 (12.0)	0.38 (30.3)	0.90 (48.3)	1.58 (67.8)
Magnetic resonance imaging[a]	17 (1.9)	41 (3.7)	65 (5.2)			
Nuclear medicine	32 (3.5)	45 (4.0)	21 (1.7)	0.17 (13.3)	0.26 (13.9)	0.19 (8.1)
Radiographs	610 (66.8)	668 (60.1)	722 (58.0)	0.17 (14.0)	0.21 (11.4)	0.22 (9.5)
Ultrasound[a]	134 (15.0)	186 (16.7)	230 (18.5)			
Total	914 (100)	1112 (100)	1245 (100)	1.24 (100)	1.86 (100)	2.34 (100)

[a] Does not use ionizing radiation.

where the cited numbers were based on a larger national sample)[9,30] and due to possible differences in age and health status among HMO enrollees (who may be healthier than non-HMO enrollees), imaging rates do seem to be lower within the included HMO settings.

We found that imaging use increased steeply with age, particularly for CT and nuclear medicine examinations, resulting in high radiation exposures received by the oldest enrollees. Among enrollees 45 years and older who underwent imaging, nearly 20% received high or very high radiation exposure annually. Although cancer risks from radiation are often considered to decline with age, recent models suggest that cancer risks decline with age until middle age, when cancer risks may then increase in a U-shaped distribution.[6,31] Thus, radiation-related cancer risks after exposure in middle and older ages may be higher than previously believed.[26] Because the utilization of imaging is higher in older adults, and because the potential harm from these tests may also be higher in these patients, it is particularly important to quantify the benefits of imaging in these patients.

We found the per capita exposure to radiation from diagnostic imaging was 2.7 mSv in 2006, similar to the annual per capita exposure reported by the National Council on Radiation Protection (NCRP), describing the entire US population[32] (3.0 mSv), and Fazel and colleagues,[11] describing a fee-for-service insured population (2.4 mSv). A notable difference is that we found a significantly larger number of patients received very high radiation exposures annually. For example, Fazel et al reported that 0.2% of insured individuals incurred a very high ($>$50 mSv) annual radiation dose, in contrast to our finding that 1.4% of enrollees received such high exposures—a 7-fold increase. There are several possible reasons for this difference, including that we did not assume that every test delivered the same radiation exposure but rather modeled the actual distribution in dose when estimating the propor-

tion of patients with high exposures. Our work adds to the work of the NCRP and Fazel et al by assessing doses limited to enrollees who underwent imaging, as it is only these individuals who are at risk of radiation-related carcinogenesis. By 2010, 10.8% of enrollees who underwent imaging received an annual exposure greater than 20 mSv. It is notable that even when limited to patients who were imaged during both time periods, the average dose per person nearly doubled, suggesting more intensive medical imaging among those who undergo any imaging.

Considering governmental limits on radiation exposure can provide context for these typical patient doses: 20 mSv is the annual allowable occupational exposure to radiation in Europe,[33,34] and 50 mSv is the annual allowable occupational exposure in the United States.[35] While it is not appropriate to set exposure limits when radiation is required for health benefit, the number of patients exposed to such levels highlights the need to consider this potential harm when ordering imaging tests and to track radiation exposures for individual patients so that this information is available to physicians who are ordering tests. The National Academy of Sciences' National Research Council concluded, after a comprehensive review of the published literature, that patients who receive radiation exposures in the same range as a single CT—10 mSv—may be at increased risk of developing cancer[6,36,37]; 16.5% of patients who underwent imaging in 2010 received a dose at least this high.

We did not assess costs for imaging within these integrated settings. Costs for imaging among fee-for-service insured elderly adults have declined since 2005, despite increasing utilization.[10,28] As part of the Deficit Reduction Act of 2005, Congress enacted a provision to equalize the reimbursement rate for imaging examinations regardless of where they were performed; among fee-for-service Medicare enrollees, a 12.7% reduction in imaging costs followed enactment.[28] Because of

bundled payments for imaging within our integrated settings, these types of per-examination reductions in payment would not be expected to have had the same effect on utilization as they have in the fee-for-service environment.[13,28]

The HMO Research Network that we relied on provides a unique opportunity to conduct analyses of patterns of imaging because of the complete capture of health care utilization by their members, including all diagnostic testing, standardization of how these data are collected, and storage of detailed imaging records so that actual radiation exposures could be measured. However, there are several limitations of our work. We focused on individuals enrolled in comprehensive health care plans and excluded data from fee-for-service enrollees because of incompleteness of the available data. For inpatient imaging examinations, only the admission date was available to us; thus, collapsing claims could lead to undercounting of multiple examinations performed during the same hospital stay. Similarly, patients who underwent multiple examinations with the same procedure code on a single day were only counted once, and for these patients we have likely underestimated their exposures. We limited assessment to beneficiaries enrolled throughout a given year, and imaging may differ for patients who leave the HMO program.

To assess medical radiation dose, we used an estimate of the dose for each patient based on a sampling of high-dose studies, but we did not use actual dose information for each individual patient examination, as these data are not routinely stored in an easily accessible format. To account for underlying variations in dose, we included an estimate of the variation in dose when estimating the number of individuals above dose thresholds, and we believe our estimates to be conservative, as they do not allow for any within-person correlation in the random deviation. We only evaluated cumulative exposure within each year and not cumulative exposure over time. We did not study cu-

mulative exposures because of the fluidity of enrollment over time. We used effective dose as the measure to summarize multiple exposures and this measure is imprecise, particularly when trying to sum across different anatomic areas that might be imaged. No alternative measure exists, and this measure will almost certainly capture those patients receiving high exposures.[38] We only assessed radiation exposure as a potential harm of testing, but there are several other potential harms associated with imaging, such as false-positive test results that may begin a cascade of unnecessary testing, and overdiagnosis of otherwise indolent disease that leads to unnecessary treatment.

The increase in use of advanced diagnostic imaging has almost certainly contributed to both improved patient care processes and outcomes, but there are remarkably few data to quantify the benefits of imaging. Given the high costs of imaging[39-41]—estimated at $100 billion annually—and the potential risks of cancer and other harms, these benefits should be quantified and evidence-based guidelines for using imaging should be developed that clearly balance benefits against financial costs and health risk.

Author Affiliations: Department of Radiology and Biomedical Imaging, Department of Epidemiology and Biostatistics, Department of Obstetrics, Gynecology, and Reproductive Sciences, University of California, San Francisco (Dr Smith-Bindman); Group Health Research Institute, Group Health Cooperative and Department of Biostatistics, University of Washington, Seattle (Dr Miglioretti and Messrs Johnson and Vanneman); Radiation Epidemiology Branch, Division of Cancer Epidemiology and Genetics, National Cancer Institute, Rockville, Maryland (Dr Lee); Institute for Health Research, Kaiser Permanente, Denver, Colorado (Dr Feigelson); Department of Radiology, Center for Health Services Research, Henry Ford Health System, Detroit, Michigan (Dr Flynn); Epidemiology Research Center, Marshfield Clinic Research Foundation, Marshfield, Wisconsin (Drs Greenlee and Kruger); Center for Health Research/Kaiser Permanente Northwest, Portland, Oregon (Drs Hornbrook and Weinmann); Center for Health Research/Kaiser Permanente Southeast, Atlanta, Georgia (Dr Roblin); HealthPartners Research Foundation, Minneapolis, Minnesota (Dr Solberg); and Center for Health Research/Kaiser Permanente Hawaii, Honolulu (Dr Williams).
Author Contributions: Dr Smith-Bindman had full access to all of the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis.
Study concept and design: Smith-Bindman, Miglioretti, Greenlee, Hornbrook.
Acquisition of data: Smith-Bindman, Miglioretti, Johnson, Feigelson, Flynn, Greenlee, Kruger, Hornbrook, Roblin, Solberg, Vanneman, Weinmann, Williams.
Analysis and interpretation of data: Smith-Bindman, Miglioretti, Johnson, Lee, Flynn, Greenlee, Kruger, Hornbrook, Solberg, Weinmann.
Drafting of the manuscript: Smith-Bindman, Miglioretti, Johnson, Hornbrook, Vanneman.
Critical revision of the manuscript for important intellectual content: Smith-Bindman, Miglioretti, Johnson, Lee, Feigelson, Flynn, Greenlee, Kruger, Hornbrook, Roblin, Solberg, Weinmann, Williams.
Statistical analysis: Smith-Bindman, Miglioretti, Johnson, Lee, Hornbrook.
Obtained funding: Smith-Bindman, Miglioretti, Greenlee, Hornbrook.
Administrative, technical, or material support: Smith-Bindman, Feigelson, Flynn, Greenlee, Kruger, Hornbrook, Vanneman, Weinmann, Williams.
Study supervision: Smith-Bindman, Miglioretti, Feigelson, Greenlee, Roblin, Williams.
Conflict of Interest Disclosures: All authors have completed and submitted the ICMJE Form for Disclosure of Potential Conflicts of Interest and none were reported.
Funding/Support: This study was supported by the National Cancer Institute–funded Cancer Research Network Across Health Care Systems (U19CA79689) and grants from the National Institutes of Health (NIH R21CA131698 and NIH K24 CA125036).
Role of the Sponsor: The funding organizations had no role in the design and conduct of the study; in the collection, analysis, and interpretation of the data; or in the preparation, review, or approval of the manuscript.
Disclaimer: The content is solely the responsibility of the authors and does not represent the official views of the National Cancer Institute or the National Institutes of Health.
Online-Only Material: The Author Video Interview and eTable are available at http://www.jama.com.
Additional Contributions: We thank the following people for their valuable assistance in gathering radiology data for this study: Julianne Endres and Deborah Seger, BA, of Group Health Research Institute; Brenda Rush, RN, and Donna Gleason of Kaiser Permanente Northwest; Autumn Deedon and Paul Hitz, BS, of Marshfield Clinic Research Foundation; Kimberly Bischoff, MSHA, from Kaiser Permanente Colorado; Ann Hanson, BS, of HealthPartners Research Foundation; Peter Joski, MSPH, of Kaiser Permanente Georgia; and Aileen Uchida, MPH, and Mark Schmidt, BA, of Kaiser Permanente Hawaii. All individuals listed were compensated for their work.

REFERENCES

1. Statement of Glenn M. Hackbarth, Chairman, Medicare Payment Advisory Commission: Options to Improve Medicare's Payments to Physicians. http://www.medpac.gov/documents/051007_Testimony_MedPAC_physician_payment.pdf. Accessed May 22, 2012.
2. Report to congressional requesters: Medicare Part B imaging services: rapid spending growth and shift to physician offices indicated need for CMS to consider additional management practices [GAO-08-452]. Government Accountability Office. http://www.gao.gov/new.items/d08452.pdf. Accessed May 16, 2012.
3. Winter A, Stensland J. Introduction: expert panel on new research on use of imaging services [presentation to Medicare Payment Advisory Commission, September 5, 2008]. http://www.medpac.gov/transcripts/imaging%20expert%20panel_Sept%2008_public.pdf. Accessed May 17, 2012.
4. Iglehart JK. Health insurers and medical-imaging policy: a work in progress. *N Engl J Med*. 2009; 360(10):1030-1037.
5. 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.
6. Preston DL, Ron E, Tokuoka S, et al. Solid cancer incidence in atomic bomb survivors: 1958-1998. *Radiat Res*. 2007;168(1):1-64.
7. Berrington de González A, Mahesh M, Kim KP, et al. Projected cancer risks from computed tomographic scans performed in the United States in 2007. *Arch Intern Med*. 2009;169(22):2071-2077.
8. Brenner DJ, Hall EJ. Computed tomography: an increasing source of radiation exposure. *N Engl J Med*. 2007;357(22):2277-2284.
9. Bhargavan M, Sunshine JH. Utilization of radiology services in the United States: levels and trends in modalities, regions, and populations. *Radiology*. 2005; 234(3):824-832.
10. Levin DC, Rao VM, Parker L. Physician orders contribute to high-tech imaging slowdown. *Health Aff (Millwood)*. 2010;29(1):189-195.
11. Fazel R, Krumholz HM, Wang Y, et al. Exposure to low-dose ionizing radiation from medical imaging procedures. *N Engl J Med*. 2009;361(9):849-857.
12. Graham S. Imaging is everything: diagnostic imaging took off a few years ago: get ready for the next wave of growth. *Baltimore Business Journal*. February 28, 2005. http://www.bizjournals.com/baltimore/stories/2005/02/28/focus1.html. Accessed May 17, 2012.
13. Hackbarth G, Reischauer R, Mutti A. Collective accountability for medical care: toward bundled Medicare payments. *N Engl J Med*. 2008;359(1):3-5.
14. Shortell SM, McCurdy RK. Integrated health systems. *Stud Health Technol Inform*. 2010;153: 369-382.
15. Lieu TA, Hinrichsen VL, Moreira A, Platt R. Collaborations in population-based health research: the 17th annual HMO Research Network Conference, March 23-25, 2011, Boston, Massachusetts, USA. *Clin Med Res*. 2011;9(3-4):137-140.
16. Hornbrook MC, Hart G, Ellis JL, et al. Building a virtual cancer research organization. *J Natl Cancer Inst Monogr*. 2005;(35):12-25.
17. Smith-Bindman R, Miglioretti DL, Larson EB. Rising use of diagnostic medical imaging in an integrated health plan. *Health Aff (Millwood)*. 2008; 27(6):1491-1502.
18. Lee C, Lodwick D, Hurtado J, Pafundi D, Williams JL, Bolch WE. The UF family of reference hybrid phantoms for computational radiation dosimetry. *Phys Med Biol*. 2010;55(2):339-363.
19. Lee C, Kim KP, Long D, et al. Organ doses for reference adult male and female undergoing computed tomography estimated by Monte Carlo simulations. *Med Phys*. 2011;38(3):1196-1206.
20. The 2007 Recommendations of the International Commission on Radiological Protection: ICRP publication 103. *Ann ICRP*. 2007;37(2-4): 1-332.
21. Murray IPC, Ell PJ, Van der Wall H. *Nuclear Medicine in Clinical Diagnosis and Treatment*. 2nd ed. New York, NY: Churchill Livingstone; 1998.
22. Hendrick RE, Pisano ED, Averbukh A, et al. Comparison of acquisition parameters and breast dose in digital mammography and screen-film mammography in the American College of Radiology Imaging Network digital mammographic imaging screening trial. *AJR Am J Roentgenol*. 2010;194(2):362-369.
23. Graubard BI, Korn EL. Predictive margins with survey data. *Biometrics*. 1999;55(2):652-659.
24. Levin DC, Rao VM, Parker L, Frangos AJ, Sunshine JH. Bending the curve: the recent marked slowdown

in growth of noninvasive diagnostic imaging. *AJR Am J Roentgenol*. 2011;196(1):W25-W29.

25. Studdert DM, Mello MM, Sage WM, et al. Defensive medicine among high-risk specialist physicians in a volatile malpractice environment. *JAMA*. 2005;293(21):2609-2617.

26. Redberg RF, Walsh J. Pay now, benefits may follow: the case of cardiac computed tomographic angiography. *N Engl J Med*. 2008;359(22):2309-2311.

27. Douglas PS. Improving imaging: our professional imperative. *J Am Coll Cardiol*. 2006;48(10):2152-2155.

28. Medicare: trends in fees, utilization, and expenditures for imaging services before and after implementation of the Deficit Reduction Act of 2005: September 26, 2008 [GAO-08-1102R]. Government Accounting Office. http://www.gao.gov/new.items /d081102r.pdf. Accessed May 18, 2012.

29. Levin DC, Bree RL, Rao VM, Johnson J. A prior authorization program of a radiology benefits management company and how it has affected utilization of advanced diagnostic imaging. *J Am Coll Radiol*. 2010;7(1):33-38.

30. Parker L, Levin DC, Frangos A, Rao VM. Geographic variation in the utilization of noninvasive diagnostic imaging: national Medicare data, 1998-

2007. *AJR Am J Roentgenol*. 2010;194(4):1034-1039.

31. Shuryak I, Sachs RK, Brenner DJ. Cancer risks after radiation exposure in middle age. *J Natl Cancer Inst*. 2010;102(21):1628-1636.

32. Ionizing radiation exposure of the population of the United States [NCRP Report No. 160]. National Council on Radiation Protection and Measurements. http://www.ncrponline.org/. Accessed March 5, 2009.

33. International basic safety standards for protection against ionizing radiation and for the safety of radiation sources. International Atomic Energy Agency. http://www-pub.iaea.org/MTCD/publications/PDF /SS-115-Web/Start.pdf. Accessed May 18, 2012.

34. International Committee on Radiological Protection. *1990 Recommendations of the International Commission on Radiological Protection: ICRP publication No. 60*. Oxford, England: Pergamom; 1991.

35. NRC Regulations (10 CFR) Part 20: standards for protection against risks: subpart C, occupational dose limits. US Nuclear Regulatory Commission. http://www .nrc.gov/reading-rm/doc-collections/cfr/part020 /part020-1201.html. Accessed September 27, 2011.

36. Charles M. UNSCEAR report 2000: sources and effects of ionizing radiation: United Nations Scien-

tific Committee on the Effects of Atomic Radiation. *J Radiol Prot*. 2001;21(1):83-86.

37. Board of Radiation Effects Research, Division on Earth and Life Sciences, National Research Council of the National Academies, Committee on the Biological Effects of Ionizing Radiation. *Health Effects of Exposure to Low Levels of Ionizing Radiation: BEIR V*. Washington, DC: National Academies Press; 1990.

38. Smith-Bindman R, Miglioretti DL. CTDIvol, DLP, and effective dose are excellent measures for use in CT quality improvement. *Radiology*. 2011;261(3):999.

39. Ensuring quality through appropriate use of diagnostic imaging [white paper]. America's Health Insurance Plans (AHIP). http://www.medsolutions.com /clinical_quality/facts/AHIP%202008%20Imaging %20Stats.pdf. Accessed May 22, 2012.

40. Glabman M. Health plans strain to contain rapidly rising costs of imaging. *Managed Care* magazine. http://www.managedcaremag.com/archives /0501/0501.imaging.html. Accessed May 22, 2012.

41. June 2010: A Data Book: Healthcare spending and the Medicare Program. Medicare Payment Advisory Commission (MEDPAC). http://www.medpac.gov /documents/jun10databookentirereport.pdf. Accessed May 22, 2012.