

## ESTIMATION OF RADIOGRAPHIC DOSES IN A CASE-CONTROL STUDY OF ACUTE MYELOGENOUS LEUKEMIA

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**Abstract**—Radiation exposure from dental and medical radiography is inherently difficult to estimate. Because no single resource is available for this type of data, gathering the information needed to estimate exposure in epidemiologic studies is a labor-intensive, imprecise process. For a case-control study of adult-onset acute myelogenous leukemia in Los Angeles County and radiography, a database was created of estimates of dose to the red bone marrow for each radiographic procedure reported by subjects in interviews and recorded in subjects' medical records. Resources used included the medical literature as well as personal communications with radiology experts. Dose estimates for each procedure based on this database are reported. Methods and complications are contrasted with a past effort to estimate dose from dental radiography for a case-control study of parotid gland tumors. Among the more difficult aspects of medical radiography dose estimation are the wide variety of examinations performed, the continually-changing environment of diagnostic imaging, and the number of variables that contribute to the delivered dose to an individual from a specific imaging procedure.

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**Key words:** leukemia; imaging; diagnostic radiology; radiation, ionizing

### INTRODUCTION

EPIDEMIOLOGIC STUDIES have associated cancers arising at various sites with past exposures to ionizing radiation. Dose-response relationships have been established, and there appears to be no threshold dose for this effect. Radiography accounts for the majority of the exposure of the U.S. population from manmade sources of ionizing radiation (National Research Council 1990; UNSCEAR

1993; IARC 2000). Therefore, it seems reasonable to investigate whether or not specific radiogenic cancers relate to prior radiographic exposures.

Unfortunately, dose-response analyses are problematic because of various difficulties inherent in retrospective dose estimation from known radiographic exposures. Because of the relative rarity of leukemia and various other radiogenic cancers, they are most easily investigated in retrospective studies. This paper will discuss the difficulties in dose estimation in such studies. It will first describe the methods used to estimate likely exposure levels in a recent study of adult-onset acute myelogenous leukemia (AML), and the estimates arrived at will be shown. Dose estimation for dental radiography in a similar retrospective study of tumors of the parotid gland will also be described, and the further difficulties that make such estimation far more difficult for medical radiography will be discussed.

### MATERIALS AND METHODS

#### Subjects

Subjects were participants in a population-based case-control study of AML designed to estimate relative risk associated with radiography in the 10 y before diagnosis. Cases were diagnosed with adult-onset AML in Los Angeles County from January 1987 through June 1994. Cases (or case proxies) for whom physician consent was received were asked to participate in the study. Each case was matched to a neighborhood control. Both cases and controls had to have resided in the U.S. during the previous 15 y to be eligible for study participation. The USC Institutional Review Board approved the study proposal and method of obtaining informed consent from study participants.

#### Interviews

Interviews were conducted from 1987 to 1997. Ascertainment of diagnostic imaging history was the major component of the 80-min, in-person interview that used a highly-structured questionnaire designed to elicit

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information about all diagnostic imaging procedures subjects had in the 10 y before diagnosis (or a comparable reference date for controls). Less detailed information about imaging procedures prior to this 10-y period was also obtained, but confirmation from medical records was sought only for the most recent 10 y. Respondents were systematically queried on a specific list of imaging procedures. For each procedure they reported having had in the 10-y period before diagnosis, they were asked the date of the procedure; the name of the procedure; the body part examined; the reason for the procedure; whether or not fluoroscopy was used; the type of facility at which the procedure was performed; and the name, address, and specialty of the health care provider who ordered the procedure. In addition, contact information was obtained about all health care providers (conventional or alternative) whom each patient saw in the 10 y before reference date whether or not the provider ordered or delivered radiographic imaging procedures. After the interview, respondents were asked to sign consent forms granting us permission to obtain information from their medical records.

### Medical records

Aggressive mail and phone techniques were used to locate as many health care providers as possible. Each provider was mailed a letter describing the study and asking for their help; a copy of the signed consent form; and a form for abstracting from their records details on diagnostic imaging procedures undergone by the subject during the 10 y of interest. Most providers chose the option offered in the letter to send photocopies of the relevant pages from the patient's record. This inquiry was limited to 10 y because the proportion of medical records available is high only for this recent period (Preston-Martin et al. 1985). The study coordinator maintained a database containing information on names of providers or facilities, provider types (e.g., chiropractor, physician, hospital, health maintenance organization), status of providers (e.g., out of practice), links to the interview questionnaire (i.e., why providers were contacted), and details of all imaging procedures abstracted from providers' records (anatomical site, procedure name, date, whether or not fluoroscopy was used). To supplement lists of providers reported by study subjects, all providers were also asked if they were aware of other providers who had treated the patient. When records had been transferred from original providers to new providers, new providers were sent consent forms and asked to provide the necessary information.

A comparison of data on radiographic exposures from personal interview vs. medical records has been done (Pogoda and Preston-Martin 2002). Data from these

two sources were used to identify the types of procedures study participants had so that likely exposures could be determined for each.

### Dosimetry

Medline was searched for articles in English on radiation dose to the red bone marrow (RBM) associated with diagnostic imaging procedures. Other resources used were the Nationwide Exposure of X-ray Trends (NEXT) surveys published by the Bureau of Radiological Health (BRH 1976–1984) and by the Conference of Radiation Control Program Directors (CRCPD 1989, 1991), the BRH publication "Organ Doses in Diagnostic Radiology," the Public Health Service and Food and Drug Administration publication "Population Exposure to X-rays, U.S. 1970" (PHSFDA 1973), the International Commission on Radiological Protection report "Protection Against Ionizing Radiation from External Sources" (ICRP 1970), the book *CRC Handbook of Radiation Doses in Nuclear Medicine and Diagnostic X-ray* (Kereiakes and Rosenstein 1980), and personal communications with radiology experts. For nuclear medicine scans, three resources were used: personal communication with a nuclear medicine expert for most likely radiopharmaceuticals used for specific procedures, the Society of Nuclear Medicine Procedure Guidelines for most likely administered activity for specific radiopharmaceuticals (SNM 2001), and the Radiation Internal Dose Information Center publication "Radiation Dose Estimates for Radiopharmaceuticals" for organ doses associated with specific radiopharmaceuticals (Stabin et al. 1996). Resources were restricted to those that specifically provided dose estimates to active red bone marrow (RBM). Because the objective was to obtain RBM dose estimates that were as stable as possible, resources were not restricted to those within the U.S. or to estimates that had been published during the range of years when subjects in the study were exposed (1977–1994). Various sites on the world wide web were also used as resources for specific details about procedures named by study respondents; e.g., different names for the same procedure or whether or not fluoroscopy was involved. Estimates of RBM dose from all resources for each imaging procedure reported in our study were entered into a database. For each procedure, an RBM dose value equal to the median estimate in our database for that procedure was assigned.

## RESULTS

The study included 412 matched case-control pairs. 1,574 and 1,446 providers were reported by 395 case and 389 control respondents, respectively (Table 1). Complete records were successfully received from 1,093 case

providers (69%) and 974 control providers (67%). On a per-subject basis, record retrieval was successful from an average of 71% of a subject's providers for both cases and controls. The most common reasons for unsuccessful record retrieval were 1) the provider claimed that they had no records for the subject (13% of all providers) and 2) inadequate information was available to locate the provider (13%). 330 cases and 316 controls had at least one diagnostic imaging procedure recorded in their medical records.

For each procedure reported in interviews or medical records, Table 2 shows the RBM dose that was assigned based on the resources detailed above. Also shown are the number of times the procedure was reported, the number of subjects for whom the procedure was reported, the resources that were available for estimating RBM dose, and the range of RBM dose estimates that were provided in the available literature. Discrepancies in numbers of procedures reported between interview and medical charts are analyzed and discussed in detail in a previously published report (Pogoda and Preston-Martin 2002). Fig. 1 shows the most frequently reported procedures across the range of RBM dose estimates. For the three most commonly reported procedures (standard chest x rays, standard spine x rays, and GI series), median RBM dose estimates based on a) U.S. "in-range," b) U.S. "out-of-range," c) non-U.S. "in-range," and d) non-U.S. "out-of-range" references are shown in Fig. 2, where "range" refers to the range of years during which study participants were exposed; e.g., "in-range" references were those published between 1978 and 1995, assuming a 1-y lag time between publication date and when the data were actually collected.

## DISCUSSION

Rounding up information to allow dose estimation in epidemiologic studies of radiographic exposures is a laborious, imprecise process requiring use of multiple information sources. The first effort at this by this group was in a study of dental radiography as a potential risk factor for subsequent development of tumors of the parotid gland (Preston-Martin et al. 1988). This effort, although time consuming and requiring considerable ingenuity, proved possible, and with the help of a dental radiologist the group was able to make reasonable assumptions and arrive at dose estimates for each type of examination-year combination (Preston-Martin et al. 1988; Preston-Martin and White 1990.) This process proved far more difficult for medical radiographic exposures. The sections below summarize the process used

for dental x-ray dosimetry and discuss why the process is far more complex for medical x-ray dosimetry.

### Dental x ray validation study

Telephone interviews (average time of 20 min) with 408 patients with primary tumors of the parotid gland and 408 individually matched controls obtained detailed lifetime history of dental care including dentists visited, radiographs taken, and conditions treated (Preston-Martin et al. 1988). A quarter of these patients (102 pairs) also participated in a validation study in which interview information was compared to information recorded in patients' dental charts; interview information was found to be unbiased and accurate enough to be used as the basis of case-control comparisons (Preston-Martin et al. 1985).

All published dosimetry surveys in the English language literature on dental and medical radiography to the head up to 1980 (5 y before the diagnosis of the most recently diagnosed case) were used to derive a model to estimate parotid exposure from each major type of radiographic procedure. Dosimetric studies are of two types: surveys of practices and dosimetry conducted in a laboratory setting. In this review findings from both types of studies were combined, as no systematic difference was found. For laboratory studies, multiple techniques were often examined, such as 65 to 90 kilovolt (peak; kVp). In these circumstances, the exposure values measured for 60–65 kVp were used as this voltage range was that most frequently used by dentists in practice.

All point estimates (year of publication or year of survey, if stated, and parotid dose) for each procedure were plotted and a regression curve was fitted relating parotid dose to calendar year (from 1920 to 1980).

**Table 1.** Final status of providers named by 395 case and 389 control respondents, case-control study of AML, Los Angeles County, 1987–1994.

Provider status	Case providers # (%)	Control providers # (%)
Complete record received from provider	1,093 (69.4)	974 (67.4)
Incomplete/inadequate file received from provider	13 (0.8)	22 (1.5)
Not enough information available to locate records	196 (12.5)	186 (12.9)
Provider retired/deceased or facility closed	14 (0.9)	30 (2.1)
Provider's records destroyed	24 (1.5)	31 (2.1)
Provider has no record of patient	205 (13.0)	189 (13.1)
Provider refused or charged excessive fee for file	17 (1.1)	8 (0.6)
Unable to obtain current patient consent	12 (0.8)	5 (0.3)
Unresolved	0 (0.0)	1 (0.1)
Total	1,574 (100.0)	1,446 (100.0)

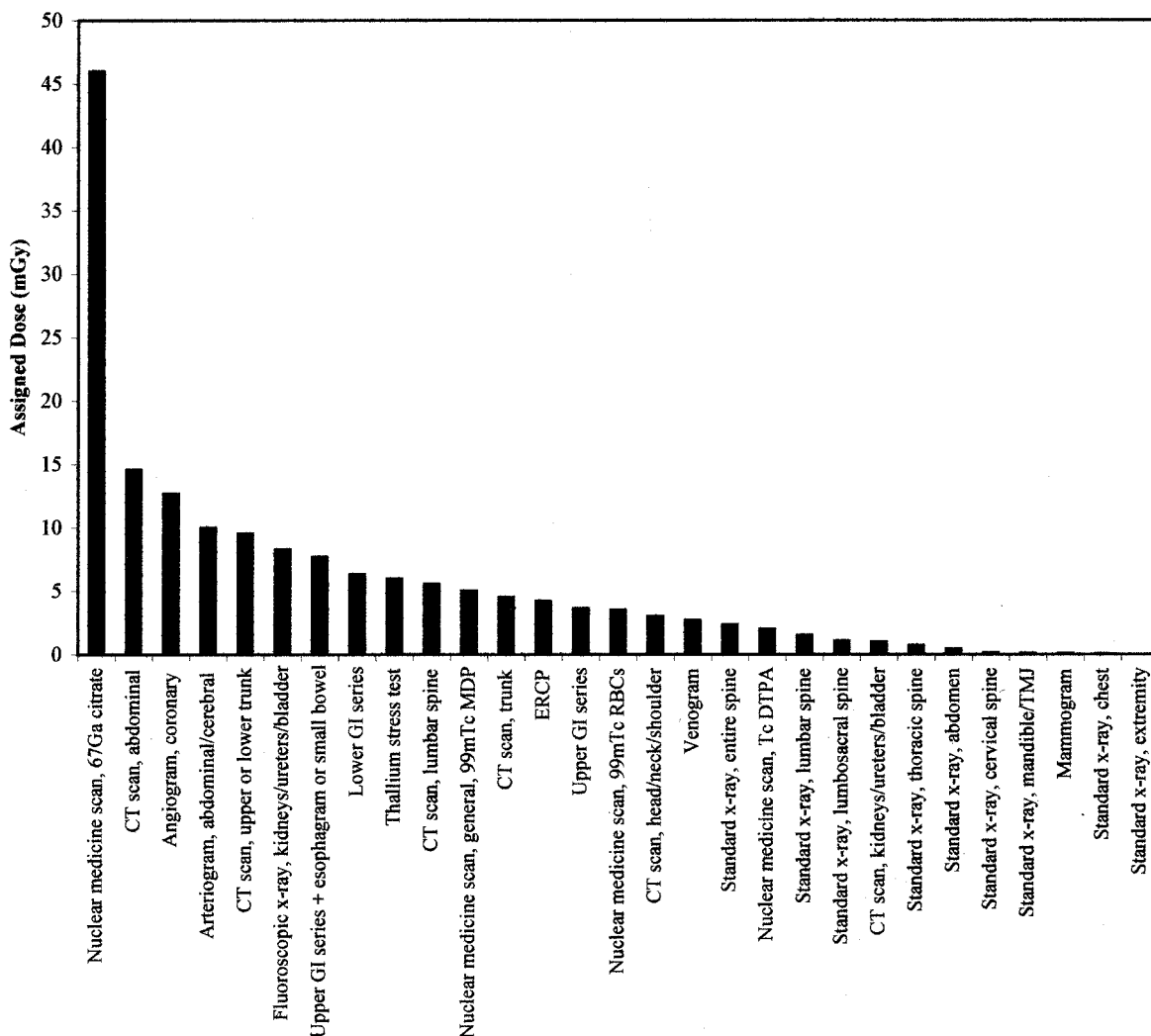


Fig. 1. Most commonly reported radiographic procedures in the Los Angeles County case-control study of AML and radiography by assigned red bone marrow (RBM) dose estimates (mGy).

Separate curves were derived for six common radiographic examinations of the head (three dental and three medical): full-mouth intraoral, panoramic, and cephalometric dental examinations; and skull series, sinus series, and computerized tomographic scans. For example, for full-mouth examinations (15 radiographs exposed on average), those surveys that measured both skin exposure and dose to the mid-parotid gland were used to estimate that the average dose to each parotid gland was 1.19% of the average skin exposure per film. This constant was then applied to the other surveys, all of which measured average skin exposure per film. Doses from periapical and bitewing radiographs were calculated using a fixed fraction of the dose from a full mouth series. For example, the exposure from bitewing examinations (four radiographs exposed) was assumed to be 4/15 of that from a full-mouth series. A similar method was used to

estimate parotid dose for each of the other radiographic procedures.

There has been considerable reduction in exposure to patients receiving dental radiographs since 1920. A main reason for this decline is the use of successively faster radiographic films—allowing a 50-fold reduction over this time period. Beam diameter, use of mechanical vs. electronic timers, and filtration are also important factors influencing patient exposure. Although information on each of these variables was not available for each dental radiographic examination over their lifetimes for patients in the parotid study, data based on sales of various speed films over time and other information about adaptation of technologic innovations support the decline in exposure per film found in the regression analyses from this study (Preston-Martin and White 1990).

**Table 2.** Number of procedures and subjects, assigned red bone marrow (RBM) dose, range of RBM doses in literature, and sources of RBM dose estimates for each procedure reported in interviews or abstracted from medical records, case-control study of AML, Los Angeles County, 1987–1994.

Procedure	Reported in interview		Abstracted from medical records		Assigned dose (mGy)	Range (mGy)	References
	No. exams	No. subjects	No. exams	No. subjects			
Angiogram, coronary	93	66	84	44	12.67	2.14–38.00	Gough et al. 1968; McNeil et al. 1985; Maccia et al. 1988; Seidnitz and Margulis 1974
Angiogram, eye	1	1	1	1	0.00	N/A	Personal communication (Louis K. Wagner)
Arteriogram, abdominal	2	2	4	4	10.00	4.81–10.00	Cohen et al. 1979; Maccia et al. 1988; Seidnitz and Margulis 1974
Arteriogram, cerebral	12	11	9	8	9.95	1.01–15.00	Bengtsson et al. 1978; Chopp et al. 1980; Chakera et al. 1982; Pavlicek et al. 1982; Maccia et al. 1988
Arteriogram, pelvic	1	1	1	1	2.10	N/A	(estimated as same as renal arteriogram)
Arteriogram, pulmonary	8	3	0	0	1.38	N/A	(estimated as same as chest fluoroscopy)
Arteriogram, renal	4	4	1	1	2.10	N/A	(estimated as same as IV pyelogram)
Arthrogram, hip	1	1	1	1	0.47	N/A	(estimated as same as fluoroscopic hip x ray)
Arthrogram, knee	27	21	14	10	0.39	N/A	(estimated as same as fluoroscopic lower leg x ray)
Arthrogram, shoulder	4	4	0	0	3.25	N/A	(estimated as same as fluoroscopic shoulder x ray)
Bone density scan	3	2	1	1	0.00	N/A	Personal communication (Louis K. Wagner)
Bone density scan (quantitative CT)	0	0	5	1	1.52	1.52–1.52	(estimated as same as lumbar spine standard x ray per Kasperczyk et al. 1991)
Bone survey	0	0	1	1	7.00	7.00–7.00	Roedler et al. 1978
C-arm, cervical spine	0	0	1	1	0.68	N/A	(estimated as same as fluoroscopic cervical spine x ray)
C-arm, lumbar spine	0	0	1	1	0.82	N/A	(estimated as same as lumbosacral C-arm)
C-arm, lumbosacral spine	0	0	1	1	0.82	N/A	(estimated as same as fluoroscopic lumbosacral spine x ray)
CT scan, abdomen	19	13	81	46	14.56	0.10–29.03	Gregg 1977; Murphy and Heaton 1985
CT scan, cervical spine	7	6	8	5	5.03	5.03–5.03	John et al. 1984
CT scan, chest	13	11	38	21	9.55	5.90–13.20	Murphy and Heaton 1985; Faulkner and Moores 1987
CT scan, colon	0	0	1	1	9.10	N/A	(estimated as same as pelvic CT scan)
CT scan, entire spine	15	13	2	2	3.92	N/A	(estimated as same as lumbosacral spine CT scan)
CT scan, extremities	1	1	0	0	0.00	N/A	(estimated as 0 since no bone marrow in extremities in adults)
CT scan, head/neck	76	57	95	62	3.00	2.20–11.83	Rosenstein 1976; Shleien et al. 1978; Faulkner and Moores 1987; Evens and Mettler 1985; Gregg 1977; Shrivastava et al. 1977; Wall et al. 1979
CT scan, hip	4	4	2	2	3.92	N/A	(estimated as same as lumbosacral spine CT scan)
CT scan, kidneys/ureters/bladder	5	5	6	3	1.00	1.00–1.00	Bankvall et al. 1982
CT scan, liver	8	6	2	2	5.47	3.40–7.54	Faulkner and Moores 1987; Vano et al. 1989
CT scan, lumbar spine	7	6	23	17	5.57	N/A	(estimated as 1.42 × lumbosacral spine CT scan)
CT scan, lumbosacral spine	3	2	18	14	3.92	3.92–3.92	John et al. 1984
CT scan, pelvis	2	2	9	5	9.10	2.50–15.70	Murphy and Heaton 1985; Faulkner and Moores 1987
CT scan, prostate	1	1	0	0	9.10	N/A	(estimated as same as pelvic CT scan)
CT scan, shoulder	1	1	0	0	3.00	N/A	(estimated as same as head/neck CT scan)
CT scan, thoracic spine	0	0	5	2	2.63	N/A	(estimated as 0.67 × lumbosacral spine CT scan)
CT scan, thoracic/cervical spine	0	0	1	1	3.50	N/A	(estimated as same as whole body CT scan)
CT scan, thoraco-lumbar spine	1	1	1	1	3.92	N/A	(estimated as same as lumbosacral spine CT scan)
CT scan, throat/thyroid	3	3	1	1	1.00	N/A	Personal communication (Louis K. Wagner)
CT scan, trunk	6	4	8	6	4.50	4.50–4.50	Murphy and Heaton 1985
CT scan, uterus/ovaries	3	1	0	0	9.10	N/A	(estimated as same as pelvic CT scan)
CT scan, whole body	28	12	1	1	3.50	3.50–4.50	Rosenstein 1976; Shleien et al. 1978; Evens and Mettler 1985
Cholangiogram	20	20	12	9	2.34	1.02–5.90	Antoku and Russell 1971; Hashizume et al. 1972; PHSFDA 1973; Rosenstein 1976; Bengtsson et al. 1978; Shleien et al. 1978; Jankowski 1984
Cholecystogram	7	7	14	14	1.59	0.66–8.47	Hashizume et al. 1972; PHSFDA 1973; Rosenstein 1976; Bengtsson et al. 1978; Shleien et al. 1978; Taylor et al. 1979; Kereiakes and Rosenstein 1980; Jankowski 1984; Shrimpton et al. 1986; Maccia et al. 1988

Table 2. Continued.

Procedure	Reported in interview		Abstracted from medical records		Assigned dose (mGy)	Range (mGy)	References
	No. exams	No. subjects	No. exams	No. subjects			
Cystogram	1	1	2	2	1.72	0.43–3.00	Bengtsson et al. 1978; Poretti 1985
ERCP	18	6	4	4	4.20	4.20–4.20	Cohen et al. 1979
Esophagram	3	3	6	6	4.05	0.09–9.40	Antoku and Russell 1971; Hashizume et al. 1972; Seidlitz and Margulis 1974; Shleien et al. 1978; McNeil et al. 1985
Fluoroscopic x ray, abdomen	1	1	1	1	6.75	4.10–9.40	Hashizume et al. 1972
Fluoroscopic x ray, cervical spine <sup>a</sup>	0	0	0	0	0.68	0.68–0.68	Jankowski et al. 1984
Fluoroscopic x ray, chest	1	1	4	4	1.38	0.26–6.00	Antoku and Russell 1971; Hashizume et al. 1972; Kitabatake et al. 1973; Shleien et al. 1978; Padovani et al. 1987
Fluoroscopic x ray, hip	1	1	0	0	0.47	0.47–0.47	Jankowski 1984
Fluoroscopic x ray, kidneys/ureters/bladder	6	5	0	0	8.30	5.00–11.60	Hashizume et al. 1972
Fluoroscopic x ray, lower extremity	0	0	2	1	0.39	0.25–0.53	Hashizume et al. 1972
Fluoroscopic x ray, lumbosacral spine <sup>a</sup>	0	0	0	0	0.82	0.82–0.82	Jankowski 1984
Fluoroscopic x ray, shoulder <sup>a</sup>	0	0	0	0	3.25	2.10–4.40	Hashizume et al. 1972
Fluoroscopic x ray, sinuses	0	0	1	1	1.70	1.70–1.70	Jankowski 1984
Hysterosalpingogram	4	3	0	0	1.98	1.03–3.98	Antoku and Russell 1971; Hashizume et al. 1972; Bengtsson et al. 1978; Maccia et al. 1988
Lower GI series	155	123	107	86	6.33	1.87–76.75	ICRP 1970; Antoku and Russell 1971; Hashizume et al. 1972; Seidlitz and Margulis 1974; Rosenstein 1976; Bengtsson et al. 1978; Shleien et al. 1978; Taylor et al. 1979; Kereiakes and Rosenstein 1980; Shrimpton et al. 1986; Padovani et al. 1987; Maccia et al. 1988; Calzado et al. 1991
Lymphangiogram	1	1	0	0	1.31	N/A	[estimated as 3 abdominal + 1 chest + 1 femoral standard x ray, per personal communication (Louis K. Wagner)]
MRI	84	71	48	33	0.00	N/A	(non-radiographic)
Mammogram	806	224	482	180	0.07	0.07–0.07	Hatzioannou et al. 2000
Myelogram, cervical spine	1	1	0	0	2.89	0.92–7.80	Antoku and Russell 1971; Hashizume et al. 1972; John et al. 1984
Myelogram, entire spine	9	6	1	1	3.70	0.35–7.80	Antoku and Russell 1971; Hashizume et al. 1972
Myelogram, lumbar spine	8	7	8	7	3.70	0.35–7.80	Antoku and Russell 1971; Hashizume et al. 1972
Myelogram, lumbosacral spine	4	2	4	4	3.70	2.15–7.80	Hashizume et al. 1972; John et al. 1984
Myelogram, thoracic/cervical spine	0	0	1	1	3.70	1.27–7.80	Antoku and Russell 1971; Hashizume et al. 1972
Myelogram, thoraco-lumbar spine	0	0	1	1	3.70	0.35–7.80	Antoku and Russell 1971; Hashizume et al. 1972
Needle localization, breast	0	0	5	4	0.07	N/A	(estimated as same as mammogram)
Needle localization, cervical spine	0	0	1	1	0.68	N/A	(estimated as same as fluoroscopic cervical spine x ray)
Needle localization, lumbar spine	0	0	2	2	0.82	N/A	(estimated as same as fluoroscopic lumbosacral spine x ray)
Needle localization, lumbosacral spine	0	0	1	1	0.82	N/A	(estimated as same as fluoroscopic lumbosacral spine x ray)
Nuclear medicine scan, GI tract (radioactive meal: <sup>99m</sup> Tc SC)	3	3	0	0	0.06	0.06–0.06	Stabin et al. 1996; SNM 2001
Nuclear medicine scan, abdomen ( <sup>67</sup> Ga citrate)	0	0	2	1	46.00	46.00–46.00	Stabin et al. 1996; SNM 2001
Nuclear medicine scan, blood-hemic system ( <sup>111</sup> In WBCs)	0	0	1	1	9.60	9.60–9.60	Stabin et al. 1996; SNM 2001
Nuclear medicine scan, bone ( <sup>67</sup> Ga citrate)	0	0	1	1	46.00	46.00–46.00	Stabin et al. 1996; SNM 2001
Nuclear medicine scan, bone ( <sup>99m</sup> Tc MDP)	6	4	41	34	5.00	5.00–5.00	Stabin et al. 1996; SNM 2001
Nuclear medicine scan, brain (Tc DTPA)	7	5	3	3	2.00	2.00–2.00	Stabin et al. 1996; SNM 2001
Nuclear medicine scan, entire spine ( <sup>99m</sup> Tc MDP)	1	1	0	0	5.00	5.00–5.00	Stabin et al. 1996; SNM 2001

Table 2. Continued.

Procedure	Reported in interview		Abstracted from medical records		Assigned dose (mGy)	Range (mGy)	References
	No. exams	No. subjects	No. exams	No. subjects			
Nuclear medicine scan, extremity ( $^{111}\text{In}$ WBCs)	0	0	1	1	9.60	9.60–9.60	Stabin et al. 1996; SNM 2001
Nuclear medicine scan, extremity ( $^{67}\text{Ga}$ citrate)	0	0	1	1	46.00	46.00–46.00	Stabin et al. 1996; SNM 2001
Nuclear medicine scan, extremity ( $^{99\text{m}}\text{Tc}$ MDP)	2	1	7	5	5.00	5.00–5.00	Stabin et al. 1996; SNM 2001
Nuclear medicine scan, gallbladder/hepatobiliary system ( $^{99\text{m}}\text{Tc}$ Hida)	0	0	3	3	0.45	0.45–0.45	Stabin et al. 1996; SNM 2001
Nuclear medicine scan, head/neck/trunk ( $^{67}\text{Ga}$ citrate)	0	0	5	5	46.00	46.00–46.00	Stabin et al. 1996; SNM 2001
Nuclear medicine scan, heart ( $^{99\text{m}}\text{Tc}$ RBCs)	15	12	17	12	3.50	3.50–3.50	Stabin et al. 1996; SNM 2001
Nuclear medicine scan, hip ( $^{99\text{m}}\text{Tc}$ MDP)	1	1	0	0	5.00	5.00–5.00	Stabin et al. 1996; SNM 2001
Nuclear medicine scan, kidneys/ureters/bladder (different isotopes)	5	4	4	3	0.60	0.02–1.43	Stabin et al. 1996; SNM 2001
Nuclear medicine scan, liver ( $^{99\text{m}}\text{Tc}$ sulfur colloid)	2	1	26	21	0.60	0.60–0.60	Stabin et al. 1996; SNM 2001
Nuclear medicine scan, lumbar spine ( $^{99\text{m}}\text{Tc}$ MDP)	0	0	1	1	4.00	4.00–4.00	Stabin et al. 1996; SNM 2001
Nuclear medicine scan, lungs ( $^{133}\text{Xe}$ )	0	0	3	3	0.09	0.09–0.09	Stabin et al. 1996; SNM 2001
Nuclear medicine scan, lungs ( $^{99\text{m}}\text{Tc}$ RBCs)	0	0	4	4	3.50	3.50–3.50	Stabin et al. 1996; SNM 2001
Nuclear medicine scan, lungs (lung perfusion: $^{99\text{m}}\text{Tc}$ MAA)	0	0	5	4	0.48	0.48–0.48	Stabin et al. 1996; SNM 2001
Nuclear medicine scan, lymphatic system ( $^{67}\text{Ga}$ citrate)	5	1	1	1	46.00	46.00–46.00	Stabin et al. 1996; SNM 2001
Nuclear medicine scan, neck (soft tissue) (Tc DTPA)	0	0	1	1	2.00	2.00–2.00	Stabin et al. 1996; SNM 2001
Nuclear medicine scan, pelvis/hips ( $^{99\text{m}}\text{Tc}$ MDP)	2	2	3	2	5.00	5.00–5.00	Stabin et al. 1996; SNM 2001
Nuclear medicine scan, prostate ( $^{99\text{m}}\text{Tc}$ MDP)	1	1	0	0	5.00	5.00–5.00	Stabin et al. 1996; SNM 2001
Nuclear medicine scan, spleen (different isotopes)	0	0	2	2	0.45	0.32–0.60	Stabin et al. 1996; SNM 2001
Nuclear medicine scan, throat ( $^{123}\text{I}$ )	12	11	9	9	0.09	0.09–0.09	Stabin et al. 1996; SNM 2001
Nuclear medicine scan, throat ( $^{99\text{m}}\text{Tc}$ )	0	0	1	1	0.72	0.72–0.72	Stabin et al. 1996; SNM 2001
Nuclear medicine scan, throat ( $^{131}\text{I}$ )	0	0	2	2	0.39	0.39–0.39	Stabin et al. 1996; SNM 2001
Nuclear medicine scan, trunk ( $^{111}\text{In}$ WBCs)	0	0	1	1	9.60	9.60–9.60	Stabin et al. 1996; SNM 2001
Nuclear medicine scan, trunk ( $^{67}\text{Ga}$ citrate)	1	1	5	4	46.00	46.00–46.00	Stabin et al. 1996; SNM 2001
Nuclear medicine scan, trunk ( $^{99\text{m}}\text{Tc}$ RBCs)	0	0	1	1	3.50	3.50–3.50	Stabin et al. 1996; SNM 2001
Nuclear medicine scan, whole body ( $^{67}\text{Ga}$ citrate)	0	0	3	2	46.00	46.00–46.00	Stabin et al. 1996; SNM 2001
Nuclear medicine scan, whole body ( $^{99\text{m}}\text{Tc}$ MDP)	11	7	9	5	5.00	5.00–5.00	Stabin et al. 1996; SNM 2001
PET scan, brain (FDG)	1	1	0	0	4.80	4.80–4.80	Stabin et al. 1996; SNM 2001
PET scan, liver (FDG)	1	1	0	0	7.20	7.20–7.20	Stabin et al. 1996; SNM 2001
Pyelogram, IV	31	27	89	73	2.10	0.02–11.60	ICRP 1970; Antoku and Russell 1971; Antoku et al. 1972; Hashizume et al. 1972; PHSFDA 1973; Rosenstein 1976; Bengtsson et al. 1978; Shleien et al. 1978; Villagran et al. 1978; Taylor et al. 1979; Kereiakes and Rosenstein 1980; Chakera et al. 1982; Shrimpton et al. 1986; Padovani et al. 1987; Contento et al. 1988; Maccia et al. 1988; Calzado et al. 1991

Table 2. Continued.

Procedure	Reported in interview		Abstracted from medical records		Assigned dose (mGy)	Range (mGy)	References
	No. exams	No. subjects	No. exams	No. subjects			
Pyelogram, retrograde	0	0	10	6	2.18	0.15–4.53	ICRP 1970; PHSFDA 1973; Bengtsson et al. 1978; Shleien et al. 1978; Wochos et al. 1979; Johnson and Goetz 1986; Maccia et al. 1988
Scanogram, abdomen	0	0	1	1	14.56	N/A	(estimated as same as abdominal CT scan)
Scanogram, blood-hemic system	0	0	1	1	3.50	N/A	(estimated as same as whole body CT scan)
Scanogram, bone	0	0	2	2	7.00	N/A	(estimated as same as bone survey)
Scanogram, lymphatic system	0	0	3	1	3.50	N/A	(estimated as same as whole body CT scan)
Scanogram, pelvis	0	0	1	1	9.10	N/A	(estimated as same as pelvic CT scan)
Small bowel series	1	1	2	2	3.50	0.29–4.22	Antoku and Russell 1971; Bengtsson et al. 1978; Shleien et al. 1978
Standard x ray, GI tract	3	3	7	5	0.71	0.71–0.71	Hashizume et al. 1972
Standard x ray, abdomen	51	39	143	90	0.42	0.11–5.12	ICRP 1970; Antoku and Russell 1971; Antoku et al. 1972; Hashizume et al. 1972; PHSFDA 1973; BRH 1976, 1977, 1978, 1979, 1980, 1981, 1982, 1983, 1984; Gregg 1977; Bengtsson et al. 1978; Shleien et al. 1978; Poretti 1985; Shrimpton and Wall 1985; Shrimpton et al. 1986; Padovani et al. 1987; Rannikko and Servomaa 1987; Contento et al. 1988; Maccia et al. 1988; CRCPD 1989, 1991
Standard x ray, acromium-clavicular joint	4	1	2	2	0.47	N/A	(estimated as mean of shoulder and clavicle standard x rays)
Standard x ray, cervical spine	47	36	136	100	0.11	0.01–0.52	Antoku and Russell 1971; Antoku et al. 1972; Hashizume et al. 1972; PHSFDA 1973; Rosenstein 1976; BRH 1976, 1977, 1978, 1979, 1980, 1981, 1982, 1983, 1984; Bengtsson et al. 1978; Shleien et al. 1978; Wochos et al. 1979; Kereiakes and Rosenstein 1980; Padovani et al. 1987; Rannikko and Servomaa 1987; Maccia et al. 1988
Standard x ray, chest	2,636	623	1,907	493	0.05	0.01–0.54	ICRP 1970; Antoku and Russell 1971; Antoku et al. 1972; Hashizume et al. 1972; PHSFDA 1973; Rosenstein 1976; BRH 1976, 1977, 1978, 1979, 1980, 1981, 1982, 1983, 1984; Gregg 1977; Bengtsson et al. 1978; Shleien et al. 1978; Archer et al. 1979; Jain et al. 1979; Taylor et al. 1979; Wochos et al. 1979; Kereiakes and Rosenstein 1980; Harrison et al. 1983; Conway et al. 1984; Jankowski 1984; Butler et al. 1985; Kumamoto 1985; Shrimpton and Wall 1985; Faulkner et al. 1986; Shrimpton et al. 1986; Padovani et al. 1987; Rannikko and Servomaa 1987; Maccia et al. 1988; CRCPD 1989; Huda et al. 1989; Leitz et al. 1990; Rueter et al. 1990; Warren-Forward et al. 1996
Standard x ray, clavicle	11	7	8	5	0.60	0.60–0.60	Bengtsson et al. 1978
Standard x ray, colon	17	2	1	1	1.30	0.71–1.88	Hashizume et al. 1972; Rannikko and Servomaa 1987
Standard x ray, entire spine	125	82	16	11	2.36	0.20–6.20	Rosenstein 1976; BRH 1976, 1977, 1978, 1979, 1980, 1981, 1982, 1983, 1984; Shleien et al. 1978; Wochos et al. 1979; Bhatnagar et al. 1981; Rao and Gregg 1984; Shrimpton et al. 1986; Padovani et al. 1987
Standard x ray, esophagus	5	1	0	0	0.47	0.47–0.47	Hashizume et al. 1972
Standard x ray, facial/nasal bones	16	14	10	9	0.13	N/A	(estimated as same as sinus standard x ray)
Standard x ray, gallbladder-biliary system	1	1	1	1	1.00	0.09–1.29	ICRP 1970; Antoku and Russell 1971; Antoku et al. 1972; Hashizume et al. 1972; Rosenstein 1976; Shleien et al. 1978; Rannikko and Servomaa 1987
Standard x ray, head/neck	14	8	0	0	0.27	0.11–0.70	ICRP 1970; Antoku and Russell 1971; Antoku et al. 1972; PHSFDA 1973; Rosenstein 1976; Shleien et al. 1978; Padovani et al. 1987
Standard x ray, heart	2	1	1	1	0.54	0.54–0.54	Bengtsson et al. 1978
Standard x ray, hip	50	35	47	32	0.42	0.06–2.13	ICRP 1970; Hashizume et al. 1972; PHSFDA 1973; Rosenstein 1976; Bengtsson et al. 1978; Shleien et al. 1978; Kereiakes and Rosenstein 1980; Padovani et al. 1987; Maccia et al. 1988

Table 2. Continued.

Procedure	Reported in interview		Abstracted from medical records		Assigned dose (mGy)	Range (mGy)	References
	No. exams	No. subjects	No. exams	No. subjects			
Standard x ray, kidneys/ureters/bladder	58	32	48	33	0.48	0.04–1.47	ICRP 1970; Hashizume et al. 1972; PHSFDA 1973; Rosenstein 1976; Shleien et al. 1978; Wochos et al. 1979; Kereiakes and Rosenstein 1980; Rannikko and Servomaa 1987; Maccia et al. 1988
Standard x ray, larynx/throat/trachea	4	4	0	0	0.11	N/A	[estimated as same as neck (soft tissue) standard x ray]
Standard x ray, lower extremity	325	131	486	196	0.00	N/A	(estimated as 0 since no bone marrow in extremities in adults)
Standard x ray, lumbar spine	111	57	67	50	1.52	0.10–4.10	ICRP 1970; Antoku and Russell 1971; Antoku et al. 1972; Hashizume et al. 1972; PHSFDA 1973; Rosenstein 1976; Bengtsson et al. 1978; Shleien et al. 1978; Villagran et al. 1978; Kereiakes and Rosenstein 1980; Harrison et al. 1983; Shrimpton and Wall 1985; Shrimpton et al. 1986; Rannikko and Servomaa 1987; Contento et al. 1988; Maccia et al. 1988
Standard x ray, lumbosacral spine	55	32	121	89	1.07	0.54–4.50	ICRP 1970; Antoku and Russell 1971; Hashizume et al. 1972; PHSFDA 1973; Rosenstein 1976; BRH 1976, 1977, 1978, 1979, 1980, 1981, 1982, 1983, 1984; Bengtsson et al. 1978; Shleien et al. 1978; Wochos et al. 1979; Kereiakes and Rosenstein 1980; Padovani et al. 1987; Contento et al. 1988; Maccia et al. 1988
Standard x ray, mandible/temporomandibular joint	10	9	5	5	0.10	0.10–0.10	Antoku and Russell 1971
Standard x ray, neck (soft tissue)	0	0	4	3	0.06	N/A	Antoku and Russell (1971) plus estimate from cervical spine standard x ray
Standard x ray, pancreas	0	0	1	1	1.00	N/A	(estimated as same as abdominal standard x ray)
Standard x ray, pelvis	27	13	48	36	0.38	0.18–1.90	ICRP 1970; Antoku and Russell 1971; Antoku et al. 1972; Hashizume et al. 1972; PHSFDA 1973; Rosenstein 1976; Bengtsson et al. 1978; Shleien et al. 1978; Kereiakes and Rosenstein 1980; Poretti 1985; Shrimpton and Wall 1985; Shrimpton et al. 1986; Padovani et al. 1987; Contento et al. 1988; Maccia et al. 1988
Standard x ray, pelvis/hips	0	0	17	15	0.60	0.39–0.81	Rosenstein 1976; Maccia et al. 1988
Standard x ray, ribs	51	38	46	33	0.38	0.01–1.43	Antoku and Russell 1971; Antoku et al. 1972; Bengtsson et al. 1978; Shleien et al. 1978; Kereiakes and Rosenstein 1980; Rannikko and Servomaa 1987
Standard x ray, sacroiliac joint	0	0	1	1	0.88	N/A	Antoku and Russell (1971) plus estimate from sacrum standard x ray
Standard x ray, sacrum/coccyx	2	2	5	5	1.70	0.88–2.51	Antoku and Russell 1971; McNeil et al. 1985
Standard x ray, scapula	2	1	8	7	0.33	N/A	(estimated as same as acromion-clavicular standard x ray)
Standard x ray, shoulder	69	54	86	65	0.06	0.02–0.60	Antoku and Russell 1971; Antoku et al. 1972; Hashizume et al. 1972; PHSFDA 1973; Bengtsson et al. 1978; Kereiakes and Rosenstein 1980; Padovani et al. 1987
Standard x ray, sinuses	55	20	63	43	0.13	0.02–1.22	Antoku and Russell 1971; Antoku et al. 1972; Bengtsson et al. 1978; Rannikko and Servomaa 1987
Standard x ray, skull	33	30	28	23	0.46	0.12–1.22	Antoku and Russell 1971; Antoku et al. 1972; Hashizume et al. 1972; PHSFDA 1973; Rosenstein 1976; BRH 1976, 1977, 1978, 1979, 1980, 1981, 1982, 1983, 1984; Gregg 1977; Bengtsson et al. 1978; Shleien et al. 1978; Wochos et al. 1979; Kereiakes and Rosenstein 1980; Harrison et al. 1983; Poretti 1985; Shrimpton et al. 1986; Maccia et al. 1988
Standard x ray, small bowel	0	0	2	2	3.50	3.50–3.50	Bengtsson et al. 1978
Standard x ray, spine (NOS)	0	0	8	8	1.41	N/A	(estimated as average of all types of spine standard x rays)

Table 2. Continued.

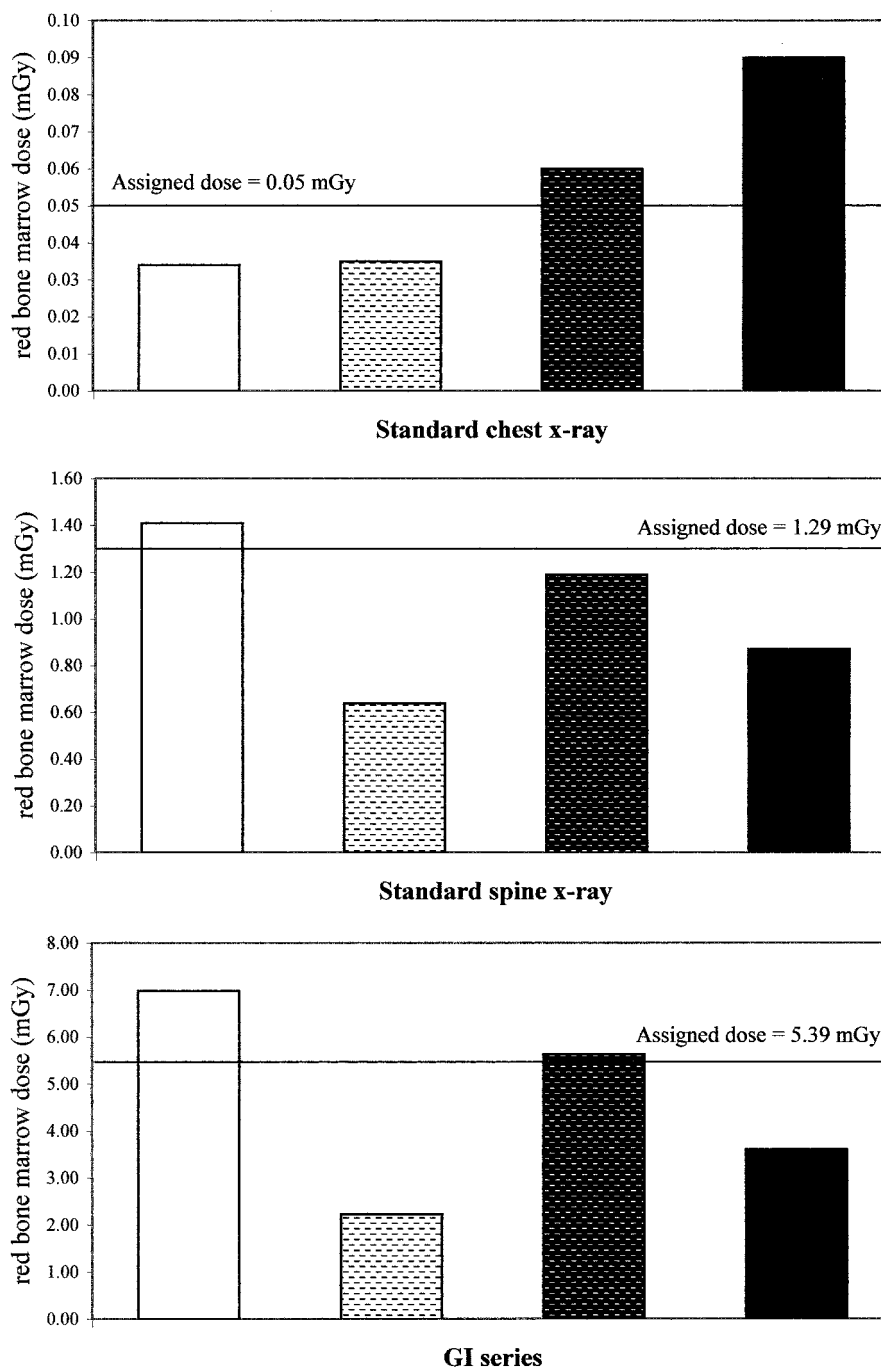
Procedure	Reported in interview		Abstracted from medical records		Assigned dose (mGy)	Range (mGy)	References
	No. exams	No. subjects	No. exams	No. subjects			
Standard x ray, sternum	0	0	12	8	0.60	0.60–0.60	Bengtsson et al. 1978
Standard x ray, thoracic spine	8	7	38	27	0.72	0.17–4.70	Antoku and Russell 1971; Antoku et al. 1972; Hashizume et al. 1972; Rosenstein 1976; BRH 1976, 1977, 1978, 1979, 1980, 1981, 1982, 1983, 1984; Bengtsson et al. 1978; Shleien et al. 1978; Wochos et al. 1979; Kereiakes and Rosenstein 1980; Poretti 1985; Shrimpton and Wall 1985; Shrimpton et al. 1986; Padovani et al. 1987; Maccia et al. 1988
Standard x ray, thoracic/cervical spine	0	0	4	4	0.42	N/A	(estimated as mean of thoracic and cervical spine standard x rays)
Standard x ray, thoraco-lumbar spine	11	7	8	5	2.39	1.69–3.09	Nash et al. 1979; Kereiakes and Rosenstein 1980; McNeil et al. 1985
Standard x ray, trunk	0	0	7	3	0.40	0.40–0.40	Hashizume et al. 1972
Standard x ray, upper extremity	274	99	236	118	0.00	N/A	(estimated as 0 since no bone marrow in extremities in adults)
Standard x ray, uterus/ovaries	3	3	0	0	0.42	N/A	(estimated as same as abdominal standard x ray)
Standard x ray, whole body	0	0	1	1	2.85	N/A	[estimated as 1 skull + 2 cervical spine + 1 rib + 1 lumbar spine + 1 pelvic standard x ray, per personal communication (Louis K. Wagner)]
Thallium stress test	11	10	27	23	6.00	6.00–6.00	Stabin et al. 1996; SNM 2001
Thermogram	2	2	4	3	0.00	N/A	(non-radiographic)
Tomogram, cervical spine	0	0	2	1	0.11	N/A	(estimated as same as cervical spine standard x ray)
Tomogram, chest	0	0	7	7	0.84	0.11–2.00	Antoku and Russell 1971; Antoku et al. 1972; Jankowski 1984
Tomogram, extremity	0	0	2	2	0.00	N/A	(estimated as 0 since no bone marrow in extremities in adults)
Tomogram, lumbosacral spine	0	0	1	1	0.52	0.32–0.71	Antoku and Russell 1971; John et al. 1984
Tomogram, sinuses	0	0	3	1	0.42	0.42–0.42	Antoku and Russell 1971
Tomogram, temporomandibular joint	0	0	3	3	0.10	N/A	(estimated as same as mandible/temporomandibular joint standard x ray)
Tomogram, thoracic spine	0	0	3	3	0.55	N/A	Antoku and Russell 1971
Ultrasound	253	100	252	148	0.00	N/A	(non-radiographic)
Upper GI series	211	158	124	92	3.64	0.66–11.80	Yoshinaga et al. 1967; ICRP 1970; Antoku and Russell 1971; Antoku et al. 1972; Hashizume et al. 1972; PHSFDA 1973; Seidlitz and Margulis 1974; Rosenstein 1976; Bengtsson et al. 1978; Shleien et al. 1978; Cohen et al. 1979; Taylor et al. 1979; Kereiakes and Rosenstein 1980; Harrison et al. 1983; Jankowski 1984; Faulkner and Bramall 1985; McNeil et al. 1985; Shrimpton et al. 1986; Padovani et al. 1987; Contento et al. 1988; Maccia et al. 1988; Calzado et al. 1991
Upper GI series + esophagram	2	2	10	10	7.69	N/A	(estimated as sum of upper GI series and esophagram)
Upper GI series + small bowel series	0	0	18	17	7.14	N/A	(estimated as sum of upper GI series and small bowel series)
Urethrogram	2	2	1	1	2.61	2.40–7.70	Hashizume et al. 1972; Bengtsson et al. 1978; Bankvall et al. 1982
Venogram	16	14	12	12	2.71	2.71–2.71	Maccia et al. 1988
Venous digital subtraction, chest/neck	0	0	1	1	6.12	6.12–6.12	Mustafa and Janeczek 1989
Ventriculogram	0	0	2	2	1.31	1.31–1.31	Antoku et al. 1972

<sup>a</sup> Not reported in interviews nor abstracted from medical records, but included because dose estimate was used for a similar procedure that was reported/abstracted.

### Further difficulties in estimating likely exposures from medical radiography

In contrast to dental radiography, medical radiography includes a huge number of different types of procedures, and

new procedures (and thus the number of procedure types) continue to proliferate. For this reason the questionnaire used in the AML study included many more questions about radiographic examinations, each with accompanying probes such as



**Fig. 2.** Median red bone marrow (RBM) dose estimates (mGy) based on □ U.S. "in-range," ▨ U.S. "out-of-range," ▩ non-U.S. "in-range," and ■ non-U.S. "out-of-range" references (in order of increasing relevance to exposure received by AML study subjects) for the three most commonly reported radiographic procedures in the Los Angeles County case-control study of AML and radiography: standard chest x ray, standard spine x ray, and GI series. Assigned RBM dose estimates (based on all geographic regions and years) used in risk analyses are annotated and depicted by horizontal lines. "Range" refers to the range of years during which study participants were exposed (1977–1994); "in-range" references were those published from 1978–1995, assuming a 1-y lag between publication and data collection. For spine x rays and GI series, median RBM dose estimates for subcategories of procedures within the broader procedure category (e.g., small bowel series was a subcategory of GI series) were averaged to arrive at overall medians.

used in the parotid study. Therefore, the AML questionnaire took on average 80 min to answer and was administered by an interviewer during a visit to patients' and controls' homes.

Unlike the situation with dental radiography, there is no similar clear trend of a declining per film exposure in recent decades, as imaging used to examine a specific organ often has changed in major ways. While radiation dose per film for a given examination may have decreased over time (although there was no specific evidence of this in the survey conducted for the AML study), for many examinations the procedure itself used to image the particular body area has changed. For example, the CT scanner, introduced in 1973, is far less invasive than many of the diagnostic procedures it replaced but also delivers higher radiation doses than standard radiographic imaging. Similarly, new applications of nuclear medicine, also associated with high radiation doses, were developed in the 1970's and 1980's. On the other hand, by the mid-1980's, MRI was available as a non-radiographic and, for many diagnostic applications, superior alternative to CT and other diagnostic procedures.

In the U.S., patients are commonly under the care of multiple health care providers (primary care physicians, specialists, chiropractors, and alternative practitioners) simultaneously. Unlike the family dentist, no one provider knows about all of the others. This was even true of patients enrolled in a health maintenance organization (HMO; Pogoda and Preston-Martin 2002). Among HMO members in the AML study, 21% received diagnostic imaging procedures outside of their HMOs constituting 43% of their total RBM dose from all radiographic imaging, and the HMOs had no records of these examinations (Pogoda and Preston-Martin 2002).

Even public agencies, which monitor radiographic equipment in use in a geographic area, do not collect items of information that are essential to calculate actual exposures to a standard patient (Mack et al. unpublished<sup>‡</sup>). For example, the Los Angeles County Radiation Management (LACRM) agency periodically surveys every radiographic machine in use in the county. LACRM data on entrance skin exposure (ESE) delivered during the three most common examinations performed with each radiographic machine were used in linear regression analyses of data on machines in use at each facility for all facility/year combinations reported by subjects in the AML study. Results indicated that the ESE varies substantially depending not only on type of x-ray machine and type of examination, but also on type of medical

facility and calendar year. Even after accounting for these measured sources of variation, there remains substantial residual variation in ESE. This variability is likely due to variation in technical factors. Unfortunately, the LACRM survey does not collect sufficient information on such factors; therefore, they could not be included in the analysis.

**Inadequacy of data recorded in patients' medical records.** Data on technical factors such as which x-ray machine was used, machine settings, and filtration are also unavailable from medical records in the U.S. Other critical factors not recorded include the time spent during fluoroscopic examinations and when it was necessary to retake certain views or entire examinations. Fluoroscopic examinations involve relatively high exposures to patients, and exposure depends directly on the time the examination takes, which in turn depends on how easily the physician can see what he or she is looking for during the examination of each patient. Time varies considerably from patient to patient even for standard fluoroscopic examinations such as upper or lower gastrointestinal examinations. The variation from physician to physician must also be considerable.

Radiographic examinations often have to be redone because the patient moves or because of errors in techniques used. Each retake doubles the exposure to the patient from that view or that examination. A patient's medical chart does not state when it was necessary to retake an examination. Retake rate could be collected by an agency such as LACRM by asking facilities to give them records of film sales to compare against radiograph billings. Toward the end of the AML study, a telephone survey of radiology departments was conducted at hospitals in Los Angeles County, and it was noted that retake rates vary considerably according to estimates provided by personnel in these departments. Information on variation in these rates over time was not available.

**Limitations in our exposure estimation.** Ideally, exposure assessment would take into account year of the procedure, facility at which the procedure was performed, the actual radiographic machine at that facility which was used for the procedure, machine settings and filtration used, number of retakes, and certain physical characteristics of the recipient of the procedure. Only the first two of these parameters are commonly recorded in patients' medical charts. Some potentially relevant survey data do exist; e.g., LACRM periodically conducts dosimetry surveys on all radiographic machines in use throughout the county. However, these survey data are collected only on the three most common examinations performed with each machine, and not all diagnostic

<sup>‡</sup> Mack WJ, Zhonghuan MA, Preston-Martin S. Variations in radiation dose from common diagnostic examinations in Los Angeles County.

procedures are covered (e.g., nuclear medicine). Therefore, survey data such as these are of limited use in assessing exposure to individual subjects who are known to have received a specific procedure at a certain facility in a specified year. Instead, the approach used in the AML study was to create a database of all procedures reported by respondents in interview and recorded in subjects' medical records and to diligently seek dose estimates from any source available for each procedure. There are several disadvantages to this approach as well. Surveys published in the medical literature are from various time periods and geographical regions, and methods of estimating dose are inconsistent across surveys. For most procedures, there was wide variation in dose estimates from different sources (Table 2). Because there were so few surveys available for any given procedure, surveys from outside the U.S. and from time periods other than those in which study subjects were exposed were also used. As demonstrated in Fig. 2, there was no clear pattern in differences in RBM dose estimates by geographic region (U.S. vs. non-U.S.) or by time period ("in-range" vs. "out-of-range" years). For very uncommon procedures for which surveys from literature were unavailable, subjective judgments from radiology experts had to be relied upon. All of these methods are extremely time-consuming and laborious; efforts to assign a dose estimate to each procedure in the database spanned several years. Finally, all dose estimates, whether from literature, experts, or radiation management surveys, are based on the "standard" patient; actual dose would depend on physical characteristics of the individual patient being examined.

## CONCLUSION

While the RBM dose estimates used for the AML study were not ideal, it is difficult to imagine a better approach that could realistically be implemented in epidemiological studies involving medical radiographic exposures in the U.S., particularly those in which exposure data are collected retrospectively. Since the goal of the analysis was to classify subjects into exposure groups (from low to high) and estimate relative risks for each group, exact exposure levels associated with each diagnostic procedure were not as important as relative exposure levels; i.e., it was critical that procedures that deliver higher doses were assigned higher exposures than those that deliver lower doses. Underestimation of exposure from various procedures is built into this approach because of inclusion of dosimetry surveys conducted in ideal laboratory settings (which are likely to be lower than those in medical care settings) and because of the lack of information on retake rate (which our survey

found can be as high as 100% for certain examinations in some facilities). It is likely that the approach used by the AML study differentiated reasonably well those procedures that delivered high rather than low doses to patients in this study, but it is also likely that the actual "doses" delivered and received are grossly underestimated.

Although thorough discussion of the relationship between RBM dose and AML risk is beyond the scope of this paper, many readers familiar with risk estimates from A-bomb survivor analyses may question the etiological relevance of estimated dose levels from radiography reported here. In fact, these exposure levels would require impractical sample sizes to detect increased AML risk based on risk models from the A-bomb survivor data. However, specific AML subtypes appear to have higher radiation-related risk than AML overall (manuscript in preparation). Further, cancer risk from low-dose radiation remains controversial and may be higher than originally thought (Zhou et al. 2001). These recent findings, along with the likely underestimation of RBM dose in the AML study, complicate comparisons between the AML study and the A-bomb survivor cohort and suggest that studies of certain AML subtypes with higher radiation-related risk may require smaller sample sizes.

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