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Estimating Historical Radiation Doses to a Cohort of U.S. Radiologic Technologists

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Data have been collected and physical and statistical models have been constructed to estimate unknown occupational radiation doses among 90,000 members of the U.S. Radiologic Technologists cohort who responded to a baseline questionnaire during the mid-1980s. Since the availability of radiation dose data differed by calendar period, different models were developed and applied for years worked before 1960, 1960–1976 and 1977–1984. The dose estimation used available film-badge measurements (approximately 350,000) for individual cohort members, information provided by the technologists on their work history and protection practices, and measurement and other data derived from the literature. The dosimetry model estimates annual and cumulative occupational badge doses (personal dose equivalent) for each technologist for each year worked from 1916 through 1984 as well as absorbed doses to organs and tissues including bone marrow, female breast, thyroid, ovary, testes, lung and skin. Assumptions have been made about critical variables including average energy of X rays, use of protective aprons, position of film badges, and minimum detectable doses. Uncertainty of badge and organ doses was characterized for each year of each technologist's working career. Monte Carlo methods were used to generate estimates of cumulative organ doses for preliminary cancer risk analyses. The models and predictions presented here, while continuing to be modified and improved, represent one of the most comprehensive dose reconstructions undertaken to date for a large cohort of medical radiation workers.

INTRODUCTION

Quantitative dose–response data are limited for populations exposed to chronic fractionated low to moderate levels of ionizing radiation. Although medical radiation workers comprise a substantial fraction of the work force exposed occupationally to ionizing radiation, there have been relatively few epidemiological investigations of cancer or other serious health risks among these workers (*1–5*), and even fewer have included dose estimates (*5–8*). Studies of non-medical nuclear workers, with extensive personal monitoring data, have been important for understanding the risks from chronic low-level radiation exposure (*9–11*).

The U.S. Radiologic Technologists (USRT)[3] cohort, assembled in the early 1980s using records of the American Registry of Radiologic Technologists, includes 146,000 technologists certified for at least 2 years during the period 1926–1982 (*12*). This unique cohort is 73% female, with a current median age of about 52 years. The National Cancer Institute is currently conducting a retrospective follow-up and assessment of mortality and radiogenic cancer risks among this group (*13*, *14*).

Cohort members first worked as radiologic technologists as long ago as 1916 or as recently as the early 1980s (Fig. 1). As explicitly shown later, the number of years worked and the decade in which a technologist worked greatly influenced the cumulative occupational dose received. Tech-

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[3] Abbreviations: AA: protective apron attenuation factor; AP: direction from which radiation is received, anterior (front) to posterior (rear); CDF: cumulative distribution function; CV: coefficient of variation; *D*: dose; DF_i: dose factor for organ 'i'; D_T: tissue dose; Floor: integer part of a real number; GM: geometric mean; GSD: geometric standard deviation; $H_p(d)$: personal dose equivalent at depth 'd'; ICRP: International Commission on Radiological Protection; K_a: air kerma; keV: kiloelectron volts; kVp: kilovolts peak; MDD: minimum detectable dose; PDF: probability density function; PHS: Public Health Service; *Q*: quality factor; R: radiation exposure (a measure of ionization of air) measured in roentgens; SI units: the International System of Units, universally abbreviated SI (from the French *Le Système International d'Unités*); the modern metric system of measurement, USRT cohort: United States Radiologic Technologist cohort.

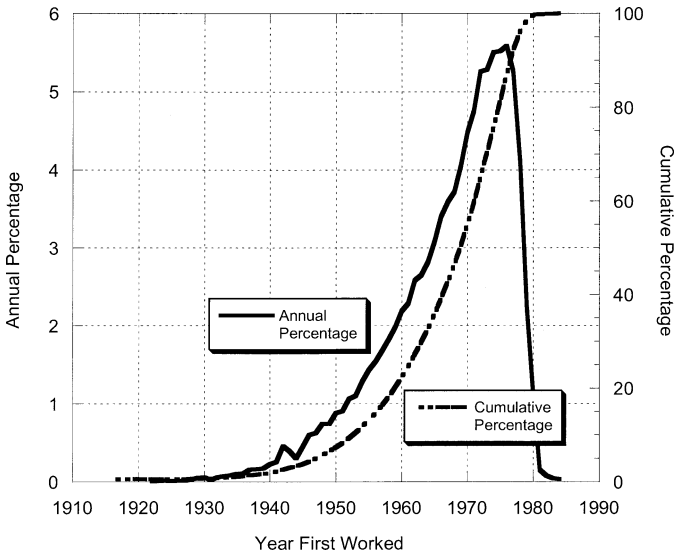

FIG. 1. Distribution of the U.S. Radiologic Technologists cohort according to the first year worked: Percentage that began working in a single year (solid line) and cumulative percentage that were working by year indicated (dotted line).

nologists who first began working prior to 1940 (n = 1,032), during 1940–1949 (n = 4,236), during 1950–1959 (n = 12,096), during 1960–1969 (n = 26,799), during 1970–1979 (n = 42,358), and during 1980–1984 (n = 1,252) had worked on average, 25, 22, 17, 14, 9 and 4 years, respectively, by the mid-1980s when a baseline questionnaire was administered. The calendar years in which USRT members worked spanned the development of modern-day radiology during which exposure to occupational radiation declined dramatically. Routine monitoring of radiation exposures to radiologic technologists first began in the late 1940s and increased dramatically through the 1950s. Work practices, procedures and protective measures also changed notably from the early part of the century to the present.

During 1983–1989, a baseline questionnaire was sent to all cohort members who could be located and were believed to be alive (n = 132,519); 90,305 (68%) technologists (including 69,525 women) responded to the questionnaire (*12, 15*). The questionnaire sought information on work history and practices, e.g., job history as a radiologic technologist, history of working with specific diagnostic procedures (such as fluoroscopy or multi-film tests), administration of radiation treatments, use of radionuclides, work practices (e.g. holding patients), use and placement of film badges, protective measures (e.g. wearing an apron), as well as history of cancer and benign tumors, selected other serious diseases, smoking history, alcohol consumption, other lifestyle characteristics, and reproductive factors (*12*). In addition, we acquired approximately 1.2 million computerized badge dose readings for individual cohort members for the period 1977–1998 from Landauer Inc., the largest commercial dosimetry provider in the U.S. Using these various data along with information derived from the literature, we undertook a historical dose assessment effort to construct estimates of annual badge dose for each of the 90,305 technologists who responded to the baseline questionnaire in each year worked from 1916 through 1984. Badge dose data were used subsequently to estimate absorbed dose to specific organs and tissues including red bone marrow, female breast, thyroid, ovary, testis, lung and skin.

Three aspects of this effort to reconstruct historical doses for radiologic technologists are notable. First, for many cohort members, particularly in the late 1970s and 1980s, person-specific film badge measurements were available and were used in part to derive individual cumulative doses. Second, detailed information on individual work history and practices was obtained from questionnaires completed by a large fraction of eligible cohort members. The key information on work practices obtained from questionnaires included protective apron use, frequency of conducting specific radiologic procedures, and other practices that could affect exposure. All of these data combined have allowed estimation of organ doses. Third, considerable attention was given to understanding and quantifying uncertainties of annual and cumulative occupational radiation doses. The dose estimation methods combine traditional dosimetric concepts and factors with numerical error propagation techniques (simulation methods) and correction for potential biases and temporal correlations.

A few epidemiological studies of radiologic technologists have been conducted to date (*15*), including follow-up investigations of radiologic technologists in the U.S. Army (*17, 18*), Chinese diagnostic X-ray workers (*3, 7, 8, 19–21*), Danish radiotherapy workers (*4*), Japanese radiologic technologists (*5, 22*), and Canadian radiation workers (*23*). Some of these studies included radiologists and other kinds of medical professionals in addition to technologists. More importantly, few had individual dose information available. Only the cohorts in Japan, China and Canada had individualized dose information, and the Canadian study did not report quantitative risk estimates or other data for radiologic technologists separately from other radiation workers.

The impetus for the detailed dosimetry described here is to support mortality and cancer risk analyses from data collected on the USRT cohort. In particular, estimated doses will allow for estimation of the dose response. The results of the historical dose reconstruction of the USRT cohort is a promising resource since so few data are available elsewhere on cancer risks associated with low to moderate fractionated exposures to ionizing radiation. Medical personnel occupationally exposed to ionizing radiation are one of the few groups available for such study.

METHODS

Overview and Objectives of Dose Assessment

The goal of the dose assessment was to create a year-by-year record of badge and organ doses, with uncertainties, for each individual cohort

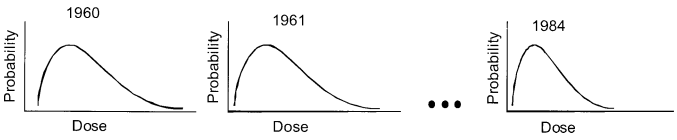

FIG. 2. Graphical representation of lognormal probability density functions describing the uncertainty in annual dose for a radiologic technologist who worked from 1960 through 1984.

member and to develop cumulative badge and organ dose uncertainty distributions for each individual. Each annual dose for a subject was not specified as a single number but rather as a probability density function (PDF) that represents the range and likelihoods of plausible values for the true annual dose. As is common in most historical dose assessments, each subject's uncertainty distribution for a single year was positively skewed. In statistical terms, the distribution shapes were lognormal. Hence, while the annual dose for a single technologist could be summarized easily by the mean or median value, in reality, many different values of doses are viewed as plausible. As an example, Fig. 2 depicts hypothetical annual uncertainty distributions of dose for a single technologist who worked from 1960 through 1984. In addition, this figure illustrates the idea that mean values of dose and uncertainty (indicated by the spread of each distribution) were lower in later years. Because the availability and quality of badge dose data differed by period, we developed different dose estimation methods for three specific periods: prior to 1960, 1960–1976 and 1977–1984. Over 17,000 cohort members (12% of the total cohort) began work prior to 1960 when occupational exposures to ionizing radiation were highest. The pre-1960 period represents about 11% of the person-years worked, the period from 1960 through 1976 represents about 49% of the person-years worked, and the period from 1977 through 1984 represents about 40% of the total person-years worked. Overall, only about 30% of the person-years had film badge measurements; hence a majority of annual exposures had to be estimated.

Estimation of Badge Doses

The data available for reconstruction of badge doses within the three periods varied considerably in quantity and quality. Details on the sources of data and the modeling and estimation procedures used for each period are provided in the following sections. Table 1 summarizes the methods and data used in the three periods.

1. Pre-1960

Actual badge dose data for the profession of radiologic technologists as a whole, and certainly for individual USRT cohort members, are sparse for the years before 1960. Our estimates of annual doses for individual USRT cohort members before 1960 are based on a synthesis of data from literature reports of personnel badge dose and other (e.g. scatter) measurements and the recommended national radiation protection standards at the time: 1934–1947, 0.2 R per day; 1947–1949, 0.5 rad per week; 1949–1958, 0.3 rad per week; and 1958–1971, 0.3 rem per week (*24*).

Through a concerted search of the peer-reviewed literature, we identified 11 publications providing quantitative film badge measurement data for the pre-1960 period; one of these provided exposure information for the period before 1940, four for the years 1940–1949, and six for the years 1950–1959.

For the years before 1960, we developed a single dose distribution for hospital technologists by decade. That distribution in turn was modified to obtain separate PDFs for physician's office technologists and for technologists who worked in both a hospital and physician's office in the same year. Badge dose PDFs were developed for 10-year periods primarily because the sparse data in the literature did not allow us to discern changes in dose over shorter periods. The period before 1940 is particularly problematic because almost no reliable information has been located. Presently, the dose distribution for each decade before 1940 is taken to be that of the 1930–1939 distribution. We are continuing to seek additional information on exposures of radiologic technologists during the early decades of the profession.

To derive decade-specific PDFs, we first evaluated the film badge data presented in the 11 publications for the decades to which they applied. Many of the publications required a degree of interpretation of the reported badge measurements because key variables (e.g., number of persons monitored or monitoring frequency) often were not stated explicitly. For example, badge dose data were frequently reported as numbers or the proportions of the total group falling within ranges of exposure. In that case, we used the midpoint of the range. When only the lower limit for the maximum exposure category was reported, we assumed a point estimate to be the sum of the lower limit of the maximum category plus half the width of the lower adjacent category. The most uncertain parameter was generally the monitoring frequency. Based on the experience at Landauer, Inc., we assumed a monitoring frequency of four badges per month per individual before 1963.

From the above considerations, a table of film badge readings from each publication was derived. The data in Table 2, derived from Spalding and Cowing (*25*), are provided as example. In that study, approximately 1,200 technologists from 106 New England area hospitals were monitored from 1950 to 1960 and about 64,000 film badges readings were collected. Restricting the data of Spalding and Cowing to the 1950–1959 period, the badge readings were derived based mainly on Figure 1 (page 500) of that paper.

Table 3 contains a summary of the data abstracted or assumed from

TABLE 1
Badge Dose Estimation by Period: Summary of Cohort Size, Sources of Data, and Estimation Methods

Pre-1960	1960–1976	1977–1984
Number of technologists that began working in period[a]		
17,364	58,911	11,4981
Person-years worked		
108,070	495,371	411,693
Sources of dosimetry data		
Film measurements and badge dose data from the literature.	Limited annual badge dose data from cohort members.	More than 350,000 badge dose measurements from cohort members.
Dose prediction methods		
Data from publications are weighted by applicability to cohort and aggregated. Distributions developed for three sub-periods (<1940, 1940–1949, 1950–1959).	Uses the same annual badge dose distribution for all years in period.	Uses loglinear predictive model when individual annual badge dose data is not available.

[a] 2,532 of 90,305 cohort member were eligible to work as a radiologic technologist but never did.

TABLE 2
Number of Badge Readings by Exposure Level (R) Derived from Spalding and Cowing (*25*) for Years 1950–1959

Year	Number of derived badge readings within exposure (R) categories[a]					
	Total number badge measurements in year	5 mR week^{-1}	50 mR week^{-1}	150 mR week^{-1}	250 mR week^{-1}	350 mR week^{-1}
1950	3,747	2,773	749	150	60	15
1951	4,051	2,593	1,134	243	57	24
1952	4,427	2,700	1,328	310	58	31
1953	5,303	3,129	1,697	212	148	117
1954	5,008	2,354	2,003	401	145	105
1955	6,655	4,126	2,063	266	80	120
1956	6,980	3,699	2,792	279	105	105
1957	7,100	3,479	3,124	284	107	107
1958	7,050	4,160	2,468	212	85	127
1959	6,560	3,805	2,296	262	85	112
Subtotal	56,881	32,817	19,654	2,619	929	862

[a] Exposure categories are midpoints of ranges reported.

the publications evaluated for the pre-1960 dose assessment. Unless specifically stated in a publication, we estimated the total number of measurements from each publication as the product of the number of personnel monitored, the time over which monitoring was conducted, and the monitoring frequency.

Tabular distributions of badge readings from monitored hospital technologists were generated for the other 10 publications. The goal was to generate decade-specific badge dose distributions for technologists working in hospitals that incorporated all the measurement data in the identified publications. The simplest approach would have been to pool all the badge measurements; however, an underlying assumption with such an approach would be that the numbers of badges from each publication were representative of the cohort in the same proportions in which they were reported. For example, the data of Hunter and Robbins (*26*) from Massachusetts General Hospital represent approximately 60% of the 1940–1949 literature badge doses; however, this is an academic hospital, with ostensibly the most progressive practices, and hence workers' exposures there were not likely representative of 60% of the entire cohort. In addition, there was a reasonable degree of variation within a given decade in the mean values reported from different publications. Consequently, we assigned a weighting factor to each publication to represent the proportion of the USRT cohort that it likely represented. The weighting factors were based on our judgment of the relevance of each paper to the cohort. In general, those papers reporting more extensive surveys were given greater weight. For example, two of the 11 publications provided data that appeared to represent large fractions of hospital technologists: ref. (*27*) for the period 1940–1949 and ref. (*25*) for the period 1950–1959. For that reason, the weighting factors (Table 3) for these two reports were considerably larger than in all others, about 0.5.

To account for subjectivity in estimating the weighting factors, each factor was defined as a range of equally probable values, equivalent to a uniform probability density function (PDF). The point estimates of the weighting factors, as discussed above, were used for the central value of the PDF (see Table 3).

The procedure to develop the hospital technologist dose distribution for each decade was as follows. A Monte Carlo simulation was performed for a specified number of trials. Here we define a *trial* as a single selection of the weighting factor from the PDF (last column, Table 3) for each publication. The weights were normalized, and a distribution of badge dose was generated from the data in each publication in proportion to the selected weights. To preserve all of the badge dose data as originally reported, the publication with the most badge doses was used in its original form, while badge dose distributions for the other publications were replicated as many times as needed, relative to their chosen weights, to achieve the desired proportions.

All of the data generated in a single trial were pooled to yield a global distribution. From that distribution, the natural logarithm ($\log_e$) of each dose was taken, and the mean and variance computed. The procedure was repeated 30 times, and the means and variances were averaged over the 30 trials. The relative mean standard error (RMSE $= [\sigma/\sqrt{n}]/\mu$) was less than 5% for the two parameters estimated (i.e. the mean and variance) with 30 trials. Exponentiation of the average mean and average standard deviation yielded a geometric mean (GM) and geometric standard deviation (GSD). Thus we preserved the $\log_e$ mean and the $\log_e$ standard deviation to develop a lognormal PDF on badge dose for hospital technologists in each decade. Differences in annual exposures in physician offices compared to hospitals were also considered. Extensive badge data from 1977–1984, as well as literature covering the 1960s (e.g. *28*) showed that the ratio of the mean dose for hospital technologists to the mean dose physician office technologists was about 1.3. Consequently, the hospital technologists' badge densities were modified by this factor to obtain physician office technologists densities.

2. 1960–1977

In this period, a small number of available cohort badge readings were used to develop a simple model. Data were obtained from two sources: (a) microfilm reels containing dosimetry reports of Landauer and (b) employers. The microfilm data were derived from 35 reels of the last-quarter reports (thus containing the cumulative annual dose) for years from 1960 to 1976. The microfilm reels yielded more than 24,000 records, of which about 2,100 could be directly matched to cohort members. Dosimetry reports were requested directly from employers of a random sample of 3,200 cohort members. The badge readings represented about 560 individuals, though they were treated as independent measurements and pooled to determine the average dose within the period.

For 1960 through 1977, we restricted the badge doses to the approximately 500 badge readings taken on the outside of the apron as reported by cohort members on the baseline questionnaire. This was done to remain consistent with the assumption used in the pre-1960 period where reported badge readings were taken to be from badges placed outside the technologists' aprons. The data indicated nearly the same average annual dose for each year (Fig. 3); therefore, we used a constant value to represent the average badge dose for each year across the entire period, modified only by type of facility where employed (hospital, physician's office, combination of workplaces).

To estimate the defining parameters of a lognormal dose distribution for a single facility type (hospital or physician's office), the overall mean and variance of the 560 readings were determined. However, estimates of the mean and variance by standard formulas were modified because

TABLE 3
Summary of Publications Used to Estimate the pre-1960 Dosimetry for the USRT Cohort

Authors, year published	Decade(s) applied to	Years of reporting (best interpretation)	Institution	Number of personnel monitored	Time of monitoring (months)	Frequency of monitoring (no. readings per month)	Total number of measurements reported	Proportion of total reported badge measurements in decade applied to (see 2nd column)	Judgment-based weighting factor uniform PDF (end points shown)
Clark and Jones, 1943 (*45*)[a]	Pre-1940	1937–1942	Physics Laboratory, Public Health Dept., London	unknown	>60	unknown	1,358 (414 indeterminate values were eliminated)	1	1
Braestrup, 1942 (*46*)[b]	1940s	1940 or 1941	Physics Laboratory, Dept. of Hospitals, New York	17	1	4	68	0.009	0.035–0.065
Hunter and Robbins, 1951 (*47*)[c]	1940s	1948–1949	Massachusetts General Hospital, Boston	55	20	4	4,400	0.61	0.08–0.12
Jamieson, 1952 (*48*)[d]	1940s	1946–1951	Dunedin Hospital, New Zealand	46	0.25	1 time only	46	0.006	0.2–0.4
Spalding *et al.*, 1949 (*49*)[e]	1940s	1948–1949	New England Deaconess Hospital	45	9	unknown	2,655	0.37	0.45–0.65
Fuller, 1966 (*50*)[f]	1950s	1956–1959	Maine Dept. of Health	434	6	2	5,208	0.14	0.1–0.2
Geist *et al.*, 1953 (*51*)[g]	1950s	3 months (1951 or 1952)	Cleveland Clinic	84	3	4	144[a]	0.0019	0.07–0.13
Godfrey *et al.*, 1957 (*52*)[h]	1950s	1954–1955 (probably)	University College Hospital, London	~76	24	4	6,160	0.083	0.07–0.13
Heustis and VanFarowe, 1951 (*53*)[i]	1950s	1 month, probably 1950	Michigan Dept. of Health (11 mental institutions)	unknown	unknown	unknown	630	0.0085	0.035–0.065
Osborn, 1955 (*54*)[j]	1950s	3 months, probably 1954	University College Hospital, London	24	3.25	4	312	0.0042	0.07–0.13
Spalding and Cowing, 1962 (*55*)[k]	1950s	1950–1959	New England Deaconess Hospital (106 hospitals)	~1,200	120	unknown	56,881	0.76	0.4–0.6

Note. References are arranged alphabetically by decade applied to.

[a] Measurements made in UK 5 years prior to publication are in percentage of 2071 films; the categories of exposure area given in proportion of daily tolerance dose (equal 0.2 R per day).

[b] Data from Physics Laboratory of Department of Hospitals, City of New York consisted of stray radiation measurements in diagnostic X-ray department.

[c] All personnel in the Department of Radiology at Massachusetts General Hospital surveyed for a 20-month period starting in 1948.

[d] All radiological personnel at Dunedin hospital in New Zealand during 1946–1951 were monitored; doses to two electricians not used.

[e] Nine-month survey of film badges worn by 45 X-ray personnel in four X-ray departments in a Boston hospital and a 3-week survey of 61 people in 13 establishments including doctors offices and X-ray departments in Boston.

[f] Data from 10 years of monitoring in the state of Maine; film badges were worn for periods of 2 weeks by groups with heavy workloads and monthly by others; majority of film badge users operated their radiographic equipment at 75 kVp.

[g] Of 84 personnel monitored, data used were restricted to 12 X-ray technicians monitored over 3 months in 1963.

[h] Study of exposures to nurses involved in radiographic procedures; included 6160 badge records over 2 years (1954–1955).

[i] Data obtained from 11 mental hospitals in Michigan where frequent holding of patients was necessary during radiographic procedures.

[j] Data from University College Hospital, London, average weekly dose over 13 weeks.

[k] Personnel monitoring records in the X-ray departments of 106 New England hospitals. Data between 1950 and 1960; derived from 64,043 films worn by approximately 1200 persons in 106 X-ray departments, each employing from 1 to 40 technicians.

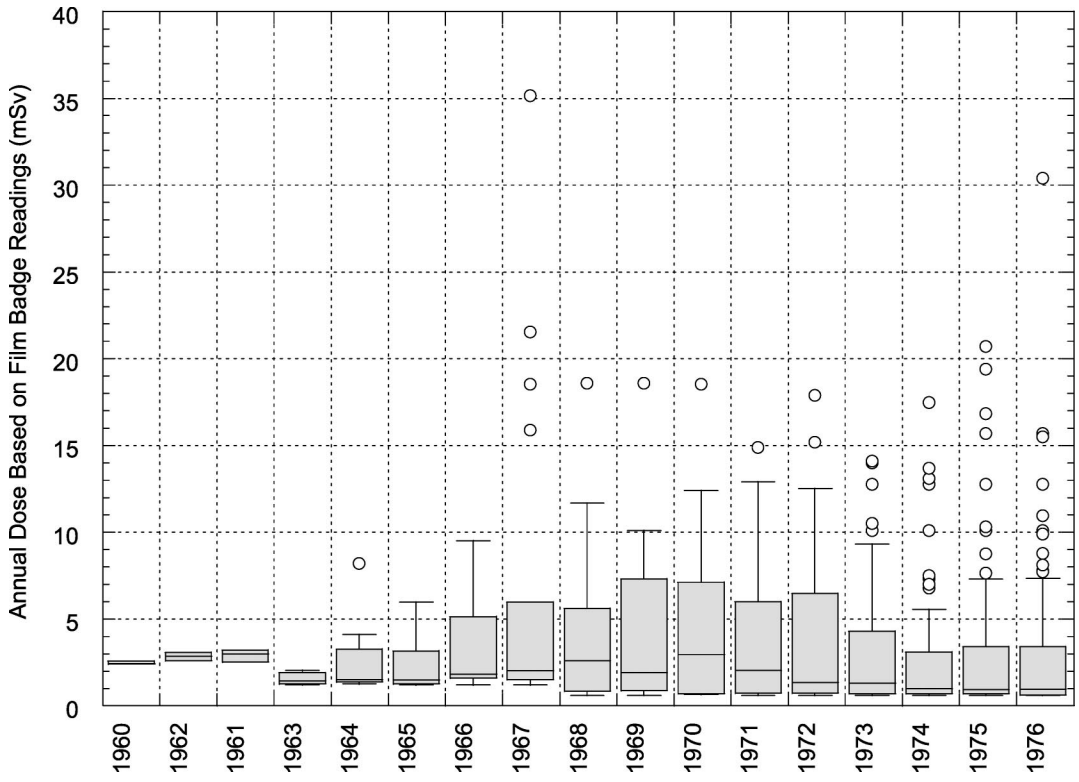

FIG. 3. Data on annual badge doses (mSv) of cohort members for the years 1960 through 1976 showing near constant average value. Data shown are from film badges worn outside of apron ($n = 468$) and include corrections for minimum detectable dose (see text). Each gray box encloses 50% of the data for that year; the horizontal bisecting line in each box is the median. The vertical line from the bottom of each box extends to the 25th percentile $-1.5 \times$ IQD and the vertical line from the top extends to the 75th percentile $+1.5 \times$ IQD. IQD is the interquartile distance and equals the difference between the 75th and 25th percentile. Outlier points beyond that range are shown as open circles.

nearly 50% of the annual dose records included a value that was likely to be underestimated assuming that the minimal detectable dose (MDD) per reporting period was 0.10 mSv. Based on experience at Landauer, Inc., 48 reporting periods were assumed for the years 1960–1962, 24 reporting periods for 1963–1967, and 12 reporting periods for 1968–1976. Annual reported doses of zero in those periods could therefore have corresponded to actual doses as high as 4.8, 2.4 and 1.2 mSv, respectively.

In practical terms, these maximum bounds are not precise, because film density (a measure of blackening due to exposure) is read in incremental units rather than as a smoothly varying quantity. In addition, film densitometers, because of limited precision, are an additional source of uncertainty. Thus a technologist with true doses in each reporting period just below the minimum detectable dose would likely have received some positive reports during the year. Such small errors in estimated doses have no substantial impact on the risk analyses that are of interest to the epidemiological study.

To estimate the mean and variance taking into account the minimum detectable dose, we used maximum likelihood estimation, including a cumulative distribution function (CDF) for a lognormal density over the values that were potentially under-reported. That is, the likelihood function has terms of CDF(D), where we assume the true dose is less than or equal to D. For a badge dose of zero, the value of D (essentially the assumed maximum credible dose) was set as 4.8, 2.4 or 1.2 mSv, as described above. Reported doses greater than zero but less than 4.8, 2.4 and 1.2 mSv in the periods 1960–1962, 1963–1967 and 1968–1976, respectively, were treated as potentially higher. In those cases, a revised dose, D (mSv), was set using the algorithm in Eq. (1):

$$D = (N - \mathit{floor}[d_r/20]) \times 10 + d_r, \tag{1}$$

where N is the number of reporting periods, *floor* is the integer part of a number (e.g., $\mathit{floor}[3.84] = 3$), and d_r is the reported dose (mSv). Note that to estimate the true dose for records with a total dose above zero but less than the product of the MDD and the number of reporting periods, the floor function rather than a rounding function was used. This ensures always rounding down to estimate the number of reporting periods for a non-MDD reading; the true dose is then less likely to be underestimated because a possible MDD period is not lost by rounding up.

The likelihood function (Eq. 2) is then

$$\mathrm{L}(d_1, d_2, \ldots, d_k, d_{k+1}, \ldots, d_n; \mu, \sigma) = \prod_{i=1}^{k} f(d_i, \mu, \sigma) \prod_{i=k+1}^{n} \mathrm{CDF}(d_i; \mu, \sigma), \tag{2}$$

where the d_i, $i \leq k$ are the reported doses, and d_i, $i > k$ is a bounding dose where the true dose, because of minimal detectable limits, is less than or equal to d_i, $i > k$. Because the CDF for a lognormal density does not have a closed form, an approximation for the function is needed. We used an open-interval extended Simpson's rule formula to approximate the integral. Another approach for estimating and incorporating doses below the minimum detectable level is a Bayesian approach with a Gibbs sampler (*29*) with γ-ray distributions could be applied; however, our likelihood estimation approach is computationally simpler, and the precision of our results is sufficient for our purposes.

The likelihood function (Eq. 2) was maximized to obtain estimates for the overall mean and variance of a dose uncertainty distribution for a single year. This PDF was applied for every year during the period 1960–

1976. The estimated overall mean population dose for the period 1960–1976 can also be expressed as

$$\mu_{\text{overall}} = aH_{\mu} + bP_{\mu} + cC_{\mu}, \quad (3)$$

where a is the percentage of hospital workers contributing to the overall mean, b is the fraction working in a physician's office, and c is the fraction of cohort members working in a combination of facility types. H_{μ}, P_{μ} and C_{μ} denote the respective means of badge dose in those groups. Letting k denote the ratio of the mean for radiologic technologists working in hospitals to the mean for those working in physicians' offices (so $H_{\mu} = kP_{\mu}$), and assuming that $C_{\mu} = 0.5H_{\mu} + 0.5\ P_{\mu}$, we have three equations in three unknowns. Solving those equations yields the mean estimate of the lognormal density function, by facility type.

The available cohort-specific badge dose readings for 1977–1984 as well as dose data available from the literature showed an estimated ratio of 1.3 for the mean dose among radiologic technologists who worked in hospitals to the mean of those who worked in physicians' offices. Values for the constants *a, b* and *c* (fractions working in hospitals, physicians' offices, combination) were taken from the self-reported questionnaire data provided by the 90,305 radiologic technologists, yielding values of $a = 0.81$, $b = 0.16$, and $c = 0.03$. We assumed that the random variables of dose for workers in a hospital or a physician's office were a constant times the random variable for the overall density function on dose, so the GSD for each was the same as the overall GSD. The group that had employment in both a hospital and a physician's office (combination group) in a given year was assumed to have the same overall GSD.

3. 1977–1984

In contrast to the two earlier periods, the dose estimation method for 1977–1984 relied heavily on personnel monitoring records from Landauer, Inc. Approximately 350,000 annual badge readings were obtained for cohort members from the computerized records of Landauer. Among the 350,000 badge readings were 208 values that were questionably high and were most likely due to improper loading of the film into the dosimeter holder. We replaced annual doses over 100 mSv (10 rem), or twice the level of the radiation protection standard at that time, with an average of the other Landauer badge doses for the individual in that period. When no other actual Landauer badge doses for an individual were available, we assigned the average annual dose of all estimated doses for the individual, based on the predictive model described below.

The 350,000 measured badge doses were used in conjunction with the self-reported work history data to develop a general linear model to predict the annual badge dose for a cohort member without measurements. The actual badge measurement was placed in an individual's year-by-year dosimetry record when available; otherwise, the dose was predicted by the model.

The predictive model developed is a generalization of

$$\log_e(D_j) = \beta_1 X_{j1} + \beta_2 X_{j2} + \cdots + \beta_k X_{jk} + \varepsilon_j, \quad (4)$$

where the β_i ($i = 1$ to k) denote the fixed effects parameters to be estimated, and j runs over the set of observed doses. However, because repeated measures are taken on the same subject over time, and these repeated measures are correlated, an additional correlation structure was imposed. More precisely, let y denote the vector of observed log-doses over a set of repeated measures for an individual, let X be the known matrix of explanatory variable values over the set, and let ε denote a covariance matrix structure; then $y = X\beta + \varepsilon$.

To develop the model, an initial set of possible predictor variables was selected using variables believed to be important in estimating the true dose an individual received. Variables included the frequency of performing specific radiologic procedures (e.g. fluoroscopy, nuclear medicine), the type of facility where the technologist worked (hospital or physician's office), the frequency of using protective measures (e.g. lead apron use), the technologist's use of certain practices (e.g. holding patients during X rays), and the technologist's gender and age in 1984 when the baseline questionnaire was administered. Three pairs of variables were highly intercorrelated: the frequency of fluoroscopy and multi-film procedures, the frequency of performing angiography and interventional radiology procedures, and the frequency of radioactive iodine treatments and other radionuclide therapies. Hence one variable from each pair was dropped from inclusion in the regression equation (Eq. 4) to estimate dose. Because 50% of the technologists had a missing or unknown value for the variable describing location of badge (under or outside an apron), we developed two models: one using badge location data and one without. For development of the models, the data sets were restricted to dose records for cohort members who had a non-missing value for every variable of interest. In this way, we could develop the most factually complete model.

Landauer identifies monthly doses for monitored workers that are below 0.1 mSv (10 mrem) as ''minimal'', i.e. below the detection limit. Since a non-negligible dose could have been accumulated, a value of 0.05 mSv (5 mrem) (one-half the detectable limit) per month or 0.6 mSv (60 mrem) per year was assumed as the dose for individuals with minimal doses. Reported doses above zero but less than 0.6 mSv, however, would then be lower than values that were revised to a dose of 0.6 mSv (originally coded as zero). To avoid that situation, for any dose less than 1.2 mSv, the following adjustment algorithm was used:

$$D = [12 - \text{floor}(d_o/12)] \times 5 + d_o, \quad (5)$$

where d_o is the original dose (mSv).

To take into account the likely correlation of annual doses over time for a given subject, the significant predictor variables were modeled further, using a repeated measures approach. The final explanatory variables and fixed effects parameter estimates (β_i values in Eq. 4) for the dosimetry model including ''badge location'' are presented in Table 4.

For individuals who worked between 1977 and 1984, but for whom there was no Landauer badge dose reported in a given year, the annual doses were predicted by one of the two models. Missing data for categorical covariates used in the models were imputed using the mode value for all cohort members; for missing continuous variables, the mean value was assigned.

Finally, to establish an uncertainty distribution for each annual badge dose within this period, two situations were considered. First, when an actual badge dose reading was available from Landauer, the uncertainty was viewed as deriving solely from laboratory measurement error inherent in film-based dosimetry. In this case, a lognormal density with a GSD of 1.2 was assumed, the rationale being that a measurement error of one standard deviation (or more precisely the 85th percentile of the lognormal uncertainty distribution) could result in a measurement being as much as 20% higher. For doses predicted by the statistical model, the uncertainty PDF was derived from the modeling error, in turn, considered to be the sum of two errors: a propagation of errors term (representing the error on the predicted mean) and the residual error. The propagation of error term was very small compared to the residual error term for each of the two loglinear models. Also, the residual error was essentially the same for both loglinear models. Thus the uncertainty about the predicted dose was taken to be the residual error, yielding on exponentiation a GSD of 2.32. That value was used as the GSD for all predicted doses in the period 1977–1984.

The two models developed for the period 1977–1984 each explained approximately 14% of the variation in measured badge doses.

Estimation of Organ Doses

Organ doses were estimated from reported ''doses'' from film badge measurements, assessed today for regulatory purposes as *personal dose equivalent* in the U.S. in units of mrem (SI units of mSv). In this work, we use the term *film badge dose* in lieu of *personal dose equivalent*, primarily because the USRT study period includes decades (i.e. before the 1960s) when film badge measurements primarily represented a measure of air ionization (roentgens) as well as at later times when the terms *deep dose, dose equivalent* and *personal dose equivalent* were used. The *personal dose equivalent* is used today as a directly measurable proxy

TABLE 4
1977–1984 Badge Dose Model: Fixed Effects Parameter Estimates

Covariate	Parameter estimate	Standard error of estimate	*P* value
Number of fluoroscopy procedures performed per year	0.0011	0.000041	<0.01
Number of routine X-ray procedures performed per year	0.00014	0.000037	<0.01
Number of other angiography procedures performed per year	0.00045	0.000062	<0.01
Number of mammography procedures performed per year	−0.0001	0.000054	0.07
Number of portable X-ray procedures performed per year	0.0002	0.000039	<0.01
Number of times held patients during a radiologic procedure per year	0.0009	0.000057	<0.01
Routinely used a lead apron (Y = 1/N = 0)	0.0002	0.000039	<0.01
Routinely wore a dosimeter on belt, waist, or side pocket (Y/N)	−0.2708	0.012	<0.01
Routinely wore a dosimeter on breast pocket (Y/N)	−0.1646	0.017	<0.01
Hospital was primary facility type (Y/N)	0.2596	0.011	<0.01
Physician's office was primary facility type (Y/N)	−0.049	0.017	<0.01
Usually wore badge under the apron (outside set to 0)	−0.2177	0.011	<0.01
Age in 1984 (years)	0.001	0.00062	0.12
Sex (F = 1/M = 0)	−0.0148	0.012	0.22
Intercept	4.688	0.028	<0.01

for *dose equivalent* in tissues and is usually derived from measurements of optical density (blackening) of film exposed in the form of badges worn on the body so that the backscatter is appropriately recorded.

1. Background and theory

In this study, estimation of organ doses involves the use of measured (or estimated) film badge reading (typically reported in units of equivalent dose) and two ratios provided by the International Commission on Radiological Protection (ICRP) (*30*): (a) the organ absorbed dose per unit of air kerma free-in-air (Gy per Gy) and (b) the personal dose equivalent per unit of air kerma free-in air (Sv per Gy). The calculation of organ absorbed dose in this study used the ICRP (*30*) factors as shown in Eq. (6).

$$D_T = H_p(d)\left[\frac{D_T}{K_a}\Big/\frac{H_p(d)}{K_a}\right], \quad (6)$$

where D_T is the tissue or organ dose (Gy or rad), $H_p(d)$ is the personal dose equivalent (Sv or rem), $d = 10$ mm for all organs but skin, where $d = 0.07$ mm, and K_a is air kerma free-in-air (usually referred to as ''air kerma'', Gy).

Table 5 provides values of D_T/K_a and $H_p(d)/K_a$ as provided by ICRP (*30*) for anterior to posterior (AP) irradiation geometry, and Fig. 4 shows D_T/K_a as a function of energy. Note that the dose factors in Table 5 are expressed in SI units (Gy and Sv) rather than traditional units (rad and rem). The values of both ratios are dependent on energy and orientation of the body with respect to the direction from which the radiation originates. We have assumed the predominant energy from diagnostic X-ray machines to be between ~30 keV and ~40 keV for X-ray beams of 75 to 120 peak voltage (kVp) (*31*); thus we used the midpoint of 35 keV. Furthermore, we assumed that most common irradiation geometry was anterior to posterior.

Personal monitoring data obtained from Landauer, Inc. and from employers was reported in units of mrem (where 1 mrem = 0.01 mSv). We have assumed those data to represent personal dose equivalent. However, publications prior to 1960 (see Table 3) reported ''doses'' in the traditional unit of air ionization, the roentgen, which is the sum of the electrical charges on ions of one sign produced in air when the electrons liberated by photons are completely stopped in a known volume of air (note that by that definition, 1 R = 2.58×10^{-4} coulombs per kg of air). Under assumptions of electronic equilibrium within the measurement volume, the air kerma (K_a) is equal to the absorbed dose to air. The dose to air per roentgen can be shown to be equal to 0.869 rad (*31*) (or K_a/X = 0.00869 Gy/R). Hence Eq. (6) can be rewritten to use exposure (R) measurements directly:

TABLE 5
Tissue and Organ Dose Coefficients in Grays per Sievert (or rad per rem) at Two Energies and Average Value of 35 keV as Used in this Study

		30 keV			40 keV			~35 keV
Organ or tissue	*d* (mm)	D_T/K_a (Gy/Gy)	$H_p(d)/K_a$ (Sv/Gy)	$(D_T/K_a)/[H_p(d)/K_a]$(Gy/Sv)	D_T/K_a (Gy/Gy)	$H_p(d)/K_a$ (Sv/Gy)	$(D_T/K_a)/[H_p(d)/K_a]$(Gy/Sv)	$(D_T/K_a)/[H_p(d)/K_a]$(Gy/Sv)
Red bone marrow	10	0.0697	1.112	0.063	0.211	1.49	0.14	0.10
Female breast	10	0.958	1.112	0.86	1.296	1.49	0.87	0.87
Thyroid	10	0.910	1.112	0.82	1.355	1.49	0.91	0.87
Ovary	10	0.158	1.112	0.14	0.511	1.49	0.34	0.24
Testes	10	1.093	1.112	0.98	1.506	1.49	1.0	0.99
Lung	10	0.297	1.112	0.27	0.693	1.49	0.47	0.37
Skin	0.07	[2 × 0.654[a]] = 1.31	1.230	~1.1[b]	[2 × 0.81[a]] = 1.62	1.444	~1.1[b]	1.1[b]

[a] The value of D_T/K_a for skin is multiplied by 2 because ICRP (*30*) averages the energy fluence over the entire skin. In this situation, the back of the body is assumed not to be exposed.

[b] For areas of skin that face the source radiation (e.g. front of face); for areas of the skin that face away from the source of radiation (e.g. back of the trunk), the value is approximated as zero.

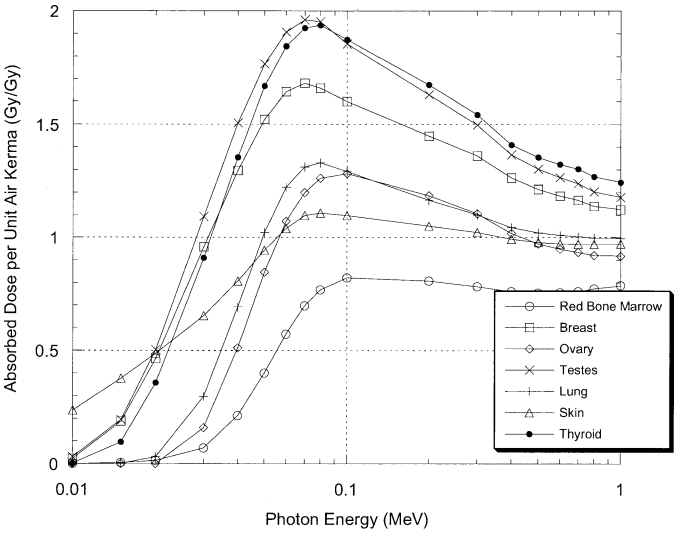

FIG. 4. Variation of the ratio of tissue dose to air kerma (D_T/K_a) as a function of X-ray energy (*30*). Values of D_T/K_a were used in Eq. (6) to estimate organ doses.

$$D_T = X\left[\frac{D_T}{K_a}\frac{K_a}{X}\right], \tag{7}$$

where X is the exposure in units of R.

Using exposure (R) measurements instead of personal dose equivalent (rem) results in a tissue dose almost equal to the numerical value of the exposure at 30 keV (actually 3% less) but about 29% higher at 40 keV (assuming a numerically equal exposure and personal dose equivalent). This can be seen by the ratio of K_a/X to $K_a/H_p(d)$ in Eqs. (8a) and (8b):

$$\frac{K_a/X}{K_a/H_p(d)} = \frac{0.869}{1/1.112} = 0.97 \quad \text{at 30 keV;} \tag{8a}$$

$$\frac{K_a/X}{K_a/H_p(d)} = \frac{0.869}{1/1.49} = 1.29 \quad \text{at 40 keV.} \tag{8b}$$

Under the present assumptions of 35 keV as the predominant energy of diagnostic radiation fields, the tissue dose would be about 13% greater (i.e. the midpoint of 0.97 and 1.29) when using exposure (R) measurements than when using the corresponding numerical value of personal dose equivalent.

Presently, we do not have information to determine the proportions of the total exposure received by individual technologists from different types of radiation sources and/or sources of different energies. Given such information, it might be possible to partition the total dose into different energy components, each with a different dose factor. Presently, however, only the dose factors for 35 keV (Table 5) are used.

It is useful to note that in the history of occupational dosimetry, it was generally assumed that 1 R = 1 rad = 1 rem. However, for the pre-1960 period, we multiplied the data reported in roentgens by 1.13 to account for the energy dependence as described above.

2. Accounting for effects of protective apron use

Badge dose estimates must be adjusted for use of protective aprons and placement of the badge relative to the apron so that the absorbed doses estimated to the organs of interest properly reflect the shielding afforded by protective aprons when they were worn. Two comprehensive questionnaires, the baseline questionnaire in the mid-1980s and the second in the mid-1990s, provided information on whether an individual technologist: (a) wore an apron when she/he first began working, (b) routinely wore an apron at the time she/he completed the baseline questionnaire, or (c) if she/he routinely wore an apron, whether she/he wore the badge outside or under the apron.

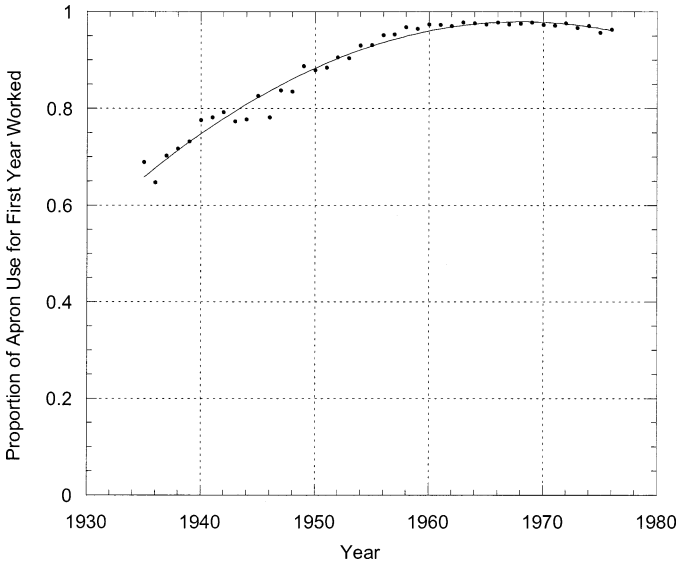

FIG. 5. Proportion of cohort that used a protective lead apron in the year he/she first worked. Fitted line is $-1135.4 + (1.15\ \text{Year}) - (0.00029 \times \text{Year}^2)$. Values along the curve are interpreted to be the ''likelihood'' of apron use for any cohort member where apron use in a specific year could not be determined. The data shown are for the period 1935–1977.

If a technologist reported wearing an apron when she/he first began working and when completing the questionnaire, we assumed that she/he always wore an apron. Likewise, if a technologist reported not wearing an apron when she/he first began working and did not routinely wear an apron at the time of the questionnaire, we assumed that she/he never wore an apron. For all others, we assigned a probability of apron use.

Specifically, the data collected from the self-administered questionnaire allowed us to formulate a discrete-valued probability density function describing the likelihood of apron protection for each individual. The density function can be defined for each year by probabilities of three mutually exclusive events: (a) did not wear an apron, (b) wore an apron and a badge outside of apron, (c) wore an apron and a badge under the apron. Let P_{NoA}, P_{AO} and P_{AU} denote the probabilities for those respective events. Thus the discrete *probability-of-protection* density function, $P_{\text{Protection}}$, can be described as

$$P_{\text{Protection}} = \begin{cases} P_{\text{NoA}} & \text{(probability of no apron)} \\ P_{\text{AO}} & \text{(probability of badge outside the apron)} \\ P_{\text{AU}} & \text{(probability of badge under the apron).} \end{cases} \tag{9}$$

To establish the values for this density function before 1977 (for a given individual in a given year), we examined the distribution of reported apron use within the cohort during the first year worked. Those data gave a profile of apron use by year for the cohort members (from 1935 through 1976). Technologists with missing values for the apron use factors were assigned probabilities for different practices, where the values of P_{NoA}, P_{AO}, and P_{AU} were based on the available cohort data for each year. Approximately 60% of technologists reported wearing an apron in 1935, and thereafter the proportion increased continuously each year. We fit a second-order polynomial to the data: $P = -1135.4 + 1.15\ \text{Year} - 0.00029\ \text{Year}^2$, where P is the proportion of the cohort that began working in that year and that routinely used an apron and Year denotes the year ($1935 < \text{Year} < 1976$.) Prior to 1935, the polynomial was not used; instead, a fixed value of 0.1 was assumed for the probability of wearing an apron. That assumption was consistent with literature indicating that few people wore aprons before 1935. For 1960–1976, a value of 0.97 is used. The proportion of radiologic technologists who used aprons, by calendar year, is shown in Fig. 5.

The method for determining the likelihood of wearing an apron, as

described above, was restricted to years prior to 1977 because we only used outside-the-apron badge dose data for that period. The data in all published reports prior to 1960 were assumed to describe measurements outside of the apron. Consequently, the probability of wearing an apron with the badge underneath was set to zero for that period. This assumption seems reasonable since the earliest measurements were from films placed not on the person but on the wall in the X-ray room. Moreover, early publications never mentioned wearing film badges under aprons.

Establishing protection probability values for the years 1977–1984 was more complex because reported doses by Landauer, as well as model-predicted doses, contain a mixture of apron use and badge location. For individuals who explicitly indicated they did not wear an apron, or individuals who wore an apron and explicitly indicated that the badge was underneath or outside the apron, then the value of the protection PDF is clearly determined. Based on the distributions of these factors among the subset of technologists who had complete information on apron and badge use, the probability of not wearing an apron (P_{NoA}) was set to 0.07, the probability of wearing an apron with the badge on the outside (P_{AO}) was set to 0.48, and the probability of wearing an apron with badge underneath (P_{AU}) was set to 0.45.

Apron attenuation describes the reduction in dose received while wearing a protective lead apron. The degree of protection afforded by an apron depends primarily on the extent of the body covered, the predominant energy of the X-ray emissions, the X-ray tube filtration, or the energy emitted from isotopes, and uniformity of the scattered radiation in the working environment. In general, higher-energy radiation results in scattered radiation of higher energy and potentially greater transmission through a lead apron of a given thickness. Typical thicknesses for lead aprons have been 0.25 mm and 0.5 mm lead equivalent. For X-ray beams of 70, 100 and 120 kVp, calculations and measurements show that lead aprons of 0.5 mm will result in a reduction in exposure of 99, 97 and 95%, respectively (*33, 34*). In this study, we assumed an 80% reduction in exposure beneath the apron (no more than 20% transmission) to account for three possibilities: (a) some aprons worn were thinner than 0.5 mm lead, (b) scattered radiation results in some exposure to parts of the body unshielded by the apron, and (c) some energies, particularly from radioisotopes, were higher than we assumed for diagnostic radiology practices. Our assumption of 20% transmission is in agreement with those of McGuire *et al.* (*35*), who studied exposures of personnel performing fluoroscopy; however, in many circumstances, aprons would be more protective than estimated.

3. Computing an organ dose

For a specific individual in a given year, each organ dose is derived from the badge dose for that year (either a measured or predicted value), the organ dose factor (Table 5), the protection PDF for that year, and the apron attenuation factor. Two equations are used, depending on whether the organ was located under the apron or outside the apron:

Organs/tissues under apron (i.e. red bone marrow, breast, lung, ovary, testis, skin of trunk):

$$\text{organ dose (mGy/year)} = BD_{m,\mathrm{sim}} \times DF_0 \times [P_{\mathrm{NoA}} + AA \times P_{\mathrm{AO}} + P_{\mathrm{AU}}]. \quad (10)$$

Organs/tissues outside apron (i.e. thyroid, skin of head/neck, and arms):

$$\text{organ dose (mGy/year)} = BD_{m,\mathrm{sim}} \times DF_{\mathrm{o}} \times [P_{\mathrm{NoA}} + P_{\mathrm{AO}} + (1/AA) \times P_{\mathrm{AU}}], \quad (11)$$

where $BD_{\mathrm{m,sim}}$ is the badge dose (either measured or simulated); DF_{o} is the dose factor for a specific organ; P_{NoA}, P_{AO}, and P_{AU} are the probabilities for not wearing an apron, wearing an apron with the badge outside, and wearing an apron with the badge underneath, respectively; and *AA* is the apron attenuation factor.

The apron attenuation factor, *AA*, in actuality is a combination of the exposure reduction afforded by wearing the apron and our interpretation of the response to the questionnaire which asked the respondent if she/he *usually* (as opposed to *always*) wore the badge either outside or under (not both) the apron. We assumed *usually* to mean 75% of the time, and from that assumption it follows that *AA* (Eq. 12) is equal to 0.4:

$$AA = [(0.2 \times 0.75) + (1 \times 0.25)] = 0.4, \quad (12)$$

where 0.2 is the fractional exposure with apron, 0.75 is the fraction of time apron is worn, 1 is the fractional exposure without an apron, and 0.25 is the fraction of time no apron is worn.

The following examples show how one can calculate two types of breast organ dose estimates: (a) a single realization (i.e. a single simulation value) of annual or cumulative breast dose from a film badge estimate, and (b) the mean breast dose in a single year or over the professional lifetime.

a. Single realization of an annual breast dose. A badge dose estimate for an individual for a specific year is first generated by Monte Carlo simulation, either from a distribution describing the measurement uncertainty of the film badge reading (i.e. GSD = 1.2) when a badge reading is available, or from the badge dose distribution developed for the cohort for that year. Let BD_{sim} denote the badge dose and let DF_{Br} and *AA* be defined as above. Choosing a random number *x* in the interval (0,1), and using the values of P_{NoA} (probability of no apron) and P_{AO} (probability of badge outside the apron) from the person's record, determine which condition of the three cases that *x* meets

$$x \leq P_{\mathrm{NoA}}; \quad \text{(a)}$$

$$P_{\mathrm{NoA}} < x \leq (P_{\mathrm{NoA}} + P_{\mathrm{AO}}); \quad \text{(b)}$$

$$x > (P_{\mathrm{NoA}} + P_{\mathrm{AO}}). \quad \text{(c)}$$

If case (a) is met, P_{NoA} is set to 1; if case (b) is met, P_{AO} is set to 1; and if case (c) is met, P_{AU} is set to 1. The other two remaining probabilities are set to zero. Equation (13) applies Eq. (10) to estimate the breast dose.

$$D_{\mathrm{breast}}\ (\mathrm{mGy}) = BD_{\mathrm{sim}} \times DF_{\mathrm{Br}} \times [P_{\mathrm{NoA}} + (AA \times P_{\mathrm{AO}}) + P_{\mathrm{AU}}]. \quad (13)$$

The above calculation can also be used to obtain a single estimate of the cumulative breast dose of a cohort member by summing the annual doses obtained using Eq. (13) over all years worked.

b. Mean breast dose. By construction, the random variables for the badge dose and apron use/badge location are independent. Thus the expected value of the breast dose distribution is the product of the expected values for those two random variables. Let BD_{mean} denote the mean badge dose, let DF_{Br} denote the breast organ dose factor, let *AA* denote the apron attenuation factor as defined above, and let [$P_{\mathrm{NoA,}}$ P_{AO} and P_{AU}] denote the respective probabilities of the discrete protection PDF. Then the mean breast dose is computed as:

$$D_{\mathrm{breast}}\ (\mathrm{mGy}) = BD_{\mathrm{mean}} \times DF_{\mathrm{Br}} \times [P_{\mathrm{NoA}} + (AA \times P_{\mathrm{AO}}) + P_{\mathrm{AU}}]. \quad (14)$$

The previous equation can also be used to obtain an individual's cumulative mean dose by computing the mean breast dose for each year and summing over all years.

Uncertainty and Dose Estimation: Simulation, Correction for Bias, and Correlation

The overall goal of the uncertainty analysis was to quantify the state of knowledge on individual organ doses, which in turn allows estimation of reasonable bounds on the population cancer risk.

We used a variety of techniques to account for and to propagate uncertainty, including analytic error propagation, simulation, temporal correlation and correction for bias. Each of these techniques is explained in some detail here. In this study, the dose estimation is not separate from the analysis of uncertainty, because the dose calculations include both aspects. Integration of dosimetry and uncertainty analysis is the accepted standard today (*36*).

Each technologist's annual badge and organ dose is characterized by a lognormal uncertainty distribution from which alternative realizations of an individual's true annual dose can be generated. Although the mathematical tractability of a lognormal density is appealing, the primary rea-

TABLE 6
Truncation Limits for Monte Carlo Simulation of Annual Badge Doses; Percentage of Hospital Worker Badge Dose Distribution less than Radiation Protection Standard and Percentage less than Truncation Limit

Period	Recommended exposure limit (mSv)	Truncation limit (mSv)	Percentage of distribution below recommended exposure limit	Percentage of distribution below 1.5 times exposure limit (truncation limit)
Prior to 1936	500	750	98.7	99.7
1936–1947	300	450	95.1 (1936–1939)	98.3 (1936–1939)
			99.9 (1940–1947)	99.99 (1940–1947)
1948–1957	150	225	99.2 (1948–1949)	99.8 (1948–1949)
			97.0 (1950–1957)	98.6 (1950–1957)
1958 and later	50	75[a]	86.5 (1958–1959)	92.0 (1958–1959)
			99.9 (1960–1976)	99.99 (1960–1976)

[a] Except for the 1977–1984 Landauer badge readings; limit there is 100 mSv.

son for developing the uncertainty densities as lognormal was that the distributions of measured doses received by cohort radiologic technologists closely fit a lognormal density.

1. Simulation

According to the methods presented for each of the three periods, a data file was developed that specified the lognormally distributed badge dose distribution for each person for each year from 1916 through 1984. If a technologist did not work in a particular year, the distribution is the degenerate zero-valued distribution. The steps to simulate yearly and cumulative badge and organ doses are outlined below. Note that in these steps, *selection* implies a Monte Carlo (numerical simulation) method.

Step I.
For a given trial, obtain values for bias correction and the weighting-error factor for the pre-1960 period.

Step II.
For a single cohort subject, for each year from 1916 to 1984:

a. Multiply the geometric mean of the annual badge dose uncertainty distribution by the bias and weighting error factor, if applicable to that year.
b. Select a value for badge dose from the annual uncertainty distribution.
c. Select a value for apron use from the discrete apron-probability distribution.
d. Compute the annual organ doses (breast, lung, etc.).

Step III.
Sum the simulated annual organ doses to obtain cumulative organ doses.

Step IV.
Repeat Step III above for each of the 90,305 cohort members. This generates estimates of annual and cumulative dose to each organ for each cohort member.

Step V.
Repeat steps I through IV n times, generating n data sets, each containing estimates of annual and cumulative dose to each organ for each cohort member.

An important issue was the maximum values allowed for the simulated dose in any given year. Since the lognormal density has a tail extending to infinity, in principle, a large value could be selected that was highly unlikely, or in the worst case, impossible. To prevent unrealistically high doses, any simulated value that exceeded 1.5 times the recommended occupational dose limit for a given year was set to 1.5 times that limit (see Table 6).

2. Correction for potential bias

As implemented in Step I of the simulation methodology, we also attempted to correct for possible bias in the geometric mean (median) of each estimated annual dose distribution. As noted earlier, all dose uncertainty distributions are lognormal with a fixed median. While there are several sources of possible bias (e.g. type of dosimeter used, calibrations), we considered the most important possible bias to be in the estimated median because our modeling using incomplete or possibly unrepresentative data may have resulted in the median being over- or underestimated for the USRT cohort.

In this study, we do not assume the GSD to be uncertain but rather to realistically describe the variability of known doses. We do assume, however, that the geometric mean (median) is uncertain, and to account for that uncertainty, we multiply it by an uncertainty distribution describing the potential bias. Using the approach of Gilbert *et al.* (*37*), we assume that the bias is lognormally distributed with a median value of unity and is a multiplicative factor on the dose.

For the pre-1960 period for which dose distributions were based on literature data, we assumed the bias probability density function to have a median of unity and a 95th percentile of 1.75. For the period 1960–1976, we used a narrower bias distribution with a median of unity and a 95th percentile of 1.5. We assumed that less bias was likely in the period after 1960 because the dose distributions were derived from cohort-specific film badge data.

In addition to corrections for possible bias of the median dose, we also attempted to correct for possible errors in the weighting factors that we assigned to the various publications for the pre-1960 period. The pre-1960 dose distributions were derived from 30 trials using uncertain weighting factors (the uncertainty of each weight characterized by a uniform probability distribution) representing the proportionate contribution of each paper's data to the overall mean. Each trial, computed with reported badge dose data for each decade prior to 1960 and a selected set of weights, ultimately yielded a distribution of doses (the distributions were on $\log_e$[dose]). The standard deviation (σ) of means from the 30 trials was used to derive the distribution describing the possible error. A multiplicative factor used to correct for possible error in the weighting factors was a lognormal density distribution with median of unity and a GSD of e^{σ}, truncated at the 5th and 95th percentiles, and denoted as W.

Thus the median (i.e. the GM) of each person's original dose probability density distribution in a given year prior to 1960, denoted here as $GM_{P,year}$, was modified as $GM_{P,year} \cdot B_i \cdot W_i$, where B_i and W_i denote the ith simulation realization (Step I of simulation methodology), and $GM_{P,year} \cdot B_i$, for the period 1960–1976.

In implementing a correction for possible *error about the median* within a given trial, we used the same randomly selected value from the bias correction distribution for the entire cohort, i.e. within a single trial, we

did not resample from the bias distribution on B, or the weighting-error distribution on W. The realizations B_i and W_i were fixed for each trial. The bias error and the weighting error were resampled, however, for each new trial.

3. Accounting for temporal correlation

To construct more realistic cumulative doses, we assumed that annual doses for an individual over successive years were correlated since there were likely to be similarities in workplace activities or conditions related to exposure (e.g., numbers and types of procedures performed annually, types of equipment used). Simulation of correlated distributions is a more complex undertaking than are independent simulations. Simple random sampling of the badge dose for each year would produce doses that are temporally independent. To achieve the desired correlation in Monte Carlo sampled doses, a rank-correlation algorithm was used to reorder the simulated values.

We analyzed the rank correlation of measured badge doses in successive years and found a consistency in the correlation coefficient within a given period. Since the uncertainty distributions for individual doses for each year worked are lognormal in form, it is reasonable and tractable to use rank correlations. During 1977–1984, the pairwise rank correlations were almost exactly 0.6, regardless of which pair of successive years was examined. Since these were the only data available, we assumed a correlation of 0.6 for doses within all successive pairs of years, regardless of the period or decade.

To implement the required reordering of sampled values to obtain the desired correlation, the rank-pairings that will yield the desired rank correlation must be determined. We used the method developed by Iman and Conover (*38*) for inducing the correlation. The Iman/Conover method provides a pairing that preserves certain desirable proprieties, for example, preserving the marginal distributions of the data. In inducing the correlation for a given individual, one starts with the first year worked and then rearranges the simulated values for each successive year up through the n trials to achieve the pairwise arrangement that maintains the desired correlation. Note that the rank pairing does not change and that each successive year's doses are rearranged in the same way, leaving the prior year's values fixed.

The steps of the Monte Carlo simulation, including the correlation modifications, can be summarized as follows. In a given trial, for each cohort member, doses are selected using Monte Carlo simulation over all years worked. The correlation method is implemented, yielding a rearrangement of doses for the n trials for an individual characterized by the specific correlation in successive years. Then the doses for each individual in each trial are summed over the years to yield a cumulative dose realization. The number of trials needed ultimately depends on the risk parameters to be estimated.

FINDINGS

Of the 90,305 technologists certified for 2 or more years by the American Registry of Radiologic Technologists through 1982 and who completed the baseline questionnaire, 2,561 never worked and were therefore assigned a zero dose. For the 87,744 technologists who worked for at least 1 year during the period 1916–1984, the dose assessment provides badge dose (mSv) uncertainty distributions for each year worked as well as annual and cumulative mean absorbed doses (mGy) to eight different organs and tissues. Organs and tissues to which doses were estimated included red bone marrow, female breast, thyroid, ovary, testes, lung and skin. A series of tables and figures summarize the findings.

Table 7 summarizes the mean and median annual badge dose (mSv) for the 87,744 exposed technologists by period and type of facility in which they worked. The estimated mean badge dose declined more than 40-fold, from 100 mSv per year from before 1940 to about 2.3 mSv per year during 1977–1984. The overall mean badge dose for hospital workers declined about 75% from the 1930s to the decades of the 1940s and 1950s. There was another 80% decline in the annual dose from about 28 mSv (on average) in the 1950s to about 3.6 mSv during the period 1960–1976.

TABLE 7
Summary of Annual Uncertainty Distributions of Badge Dose (mSv) for USRT Study Assigned to each Cohort Member

Calendar period	Facility type	Median[a]	Mean[a]	GSD[b]
≤1939	Hospital	71	100	2.4
	Physician's office	54	80	2.4
	Combination	62	92	2.4
	Other	62	92	2.4
1940–1949	Hospital	16	25	2.5
	Physician's office	13	19	2.5
	Combination	15	22	2.5
	Other	15	22	2.5
1950–1959	Hospital	11	28	3.9
	Physician's office	8.6	22	3.9
	Combination	9.9	25	3.9
	Other	9.9	25	3.9
1960–1976	Hospital	2.2	3.6	2.7
	Physician's office	1.6	2.6	2.7
	Combination	1.9	3.0	2.7
	Other	1.9	3.0	2.7
1977–1984	Hospital	2.0	2.3	2.3
	Physician's office	1.1	1.3	2.3
	Combination	1.4	1.6	2.3
	Other	1.2	1.5	2.3

[a] Median and mean are based on model predictions (only) within each period prior to 1977. For 1977–1984, mean and median includes both film-badge measurements and model predictions.

[b] Value of GSD for all periods is based on variability of model predictions among cohort members working during the specific period. If subject had a film badge measurement, the GSD is assumed to be 1.2.

The uncertainty distributions on individual badge doses were assumed as lognormal distributions. The GSD (Table 7) describes the uncertainty of individual doses except when an actual film badge measurement was available, whereupon the GSD was assumed to be equal to 1.2 (see footnote b, Table 7).

Figure 6 presents the empirical CDF of cumulative mean badge dose (mSv) for all exposed technologists in the cohort. Cumulative mean badge doses ranged from 1 mSv to 2658 mSv; the mean and median were 63.8 and 28.7 mSv, respectively. The standard deviation was wide (119 mSv) because the average badge dose changed over time as a consequence of changes in technology and medical techniques, the number of years each technologist worked, and the tasks performed by each technologist.

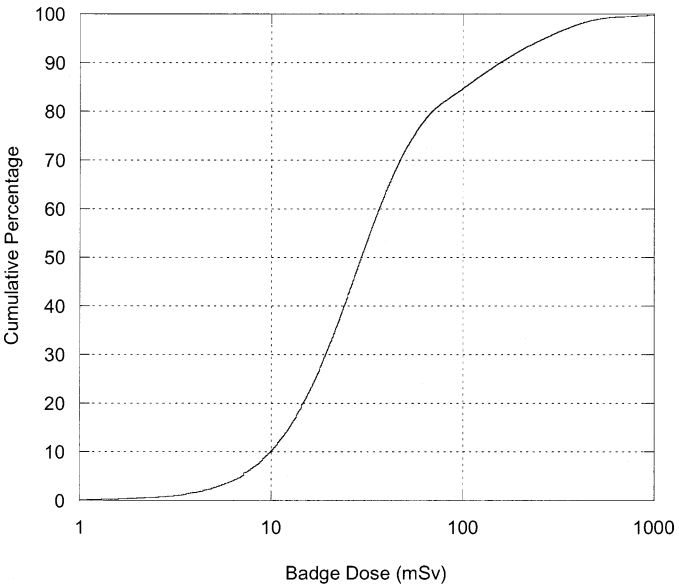

FIG. 6. CDF of cumulative mean badge doses (mSv) for 87,744 radiologic technologists with non-zero doses.

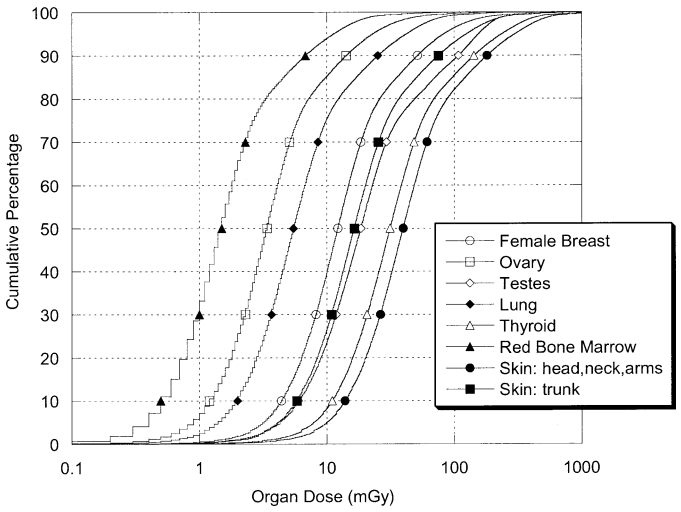

FIG. 7. CDFs of cumulative mean organ doses (mGy) for radiologic technologist cohort. The number of exposed technologists can be found in Table 7.

Table 8 presents summary statistics for cumulative mean organ doses (mGy) (i.e., a summation of each individual's mean organ dose value over years worked) for the period 1916–1984. For other than gender-specific organs, 87,744 cumulative mean dose estimates were computed. The numbers of estimated doses to the female breast, ovary and testes reflect the exposed cohort proportions of about 77% female and 23% male. The population-mean value for any organ/tissue dose varies with the depth of the organ within the body and the proportion of technologists who wore protective aprons. In general, the skin of the head, neck and arms was estimated to have received the highest cumulative dose (about 80 mGy, on average). The thyroid received the next highest cumulative dose (62 mGy), followed by the testes (40 mGy), skin on the trunk (33 mGy), female breast (24 mGy), lung (11 mGy), ovary (6.6 mGy), and red bone marrow (3 mGy). The coefficients of variation (CVs) for most organs/tissues were similar (~1.7 to 2.0). The CV for skin of the head, neck, and arms was modestly less (1.6), primarily because the variation among technologists in the use of protective clothing did not affect its estimation. Figure 7 presents the CDF of cumulative mean doses received by organ or tissue site which are summarized in Table 8. For some organs, the maximum values are not shown but can be found in Table 8.

Table 9 summarizes estimates of cumulative mean breast dose (mGy) for female technologists according to the decade in which they began working. As expected, the cumulative mean breast dose decreased over time, with the most dramatic changes, in absolute terms, taking place during the earlier decades. Between 1916–1939 and 1940–1949, the estimated cumulative dose to the breast fell from about 320 mGy on average to 98 mGy on average; thereafter the mean dose declined by 50% or more between the years 1940–1949 and 1950–1959 and between 1950–1959 and 1960–1969. The declines in mean average dose were smaller between 1960–1969 and 1970–1979 and between 1970–1979 and 1980–1989. The coefficient of variation did not differ over time in any systematic way, varying between 0.5 and 0.75 for different decades. Figure 8 is a companion to Table 9 and presents the CDFs for cumulative mean breast dose by decade when first began working. The or-

TABLE 8
Summary Statistics on Estimated Cumulative Mean Organ Doses (mGy) over all Years Worked (1916–1984)

	Female breast dose (mGy)	Ovary dose (mGy)	Testis dose (mGy)	Lung dose (mGy)	Thyroid dose (mGy)	Red bone marrow (mGy)	Skin dose: trunk (mGy)	Skin dose: head, neck, arms (mGy)
Number of technologists	67,736	67,724	20,008	87,742	87,744	87,652	87,744	87,744
Minimum	0.1	0.1	0.1	0.1	0.2	0.1	0.1	0.2
Maximum	1,900	530	2,020	820	2,300	220	2,400	2,900
Median	12	3.4	19	5.5	31	1.5	16	40
Mean	24	6.6	40	11	62	3	33	79
Standard deviation	47	13	67	21	105	5.8	64	130
Coefficient of variation	2.0	2.0	1.7	1.9	1.7	1.9	1.9	1.6

Note. Summary statistics are for non-zero values only.

TABLE 9
Summary Statistics on Estimated Cumulative Mean Female Breast Dose (mGy) by Decade First Worked

	1916–1939	1940–1949	1950–1959	1960–1969	1970–1979	1980–1984
Number of female technologists	792	2,769	9,144	21,391	32,634	1,025
Minimum	7.3	1.9	1.3	0.1	0.1	0.2
Maximum	1,900	410	370	130	180	36
Median	260	94	44	14	9.0	3.2
Mean	320	98	49	15	10	4.0
Standard deviation	220	50	26	9.1	7.5	3.4
Coefficient of variation	0.69	0.51	0.53	0.61	0.75	0.50

dering of the CDF curves from left to right is the same as the order of median doses in Table 9.

DISCUSSION

For the first time, both annual and cumulative occupationally received individual radiation doses have been estimated for eight specific organs and tissues for a large group of radiologic technologists working in the U.S. since the early decades of the twentieth century until the mid-1980s. All doses are presented as uncertainty distributions rather than only as point estimates.

The key aspect of the dosimetry has been the focus on obtaining or estimating individual film badge measurements and using those data to estimate individual organ doses as well as realistically accounting for important modifying factors, e.g. the use of protective aprons. In addition, we developed different dose prediction models for different periods using the most relevant data for those years. The dosimetry reconstruction uses a comprehensive approach to identifying and propagating uncertainty and adjustment for temporal correlations and bias in model parameter estimates. These various techniques are not novel in isolation but have not been combined previously on this scale, particularly for a cohort occupationally exposed to fractionated doses of ionizing radiation.

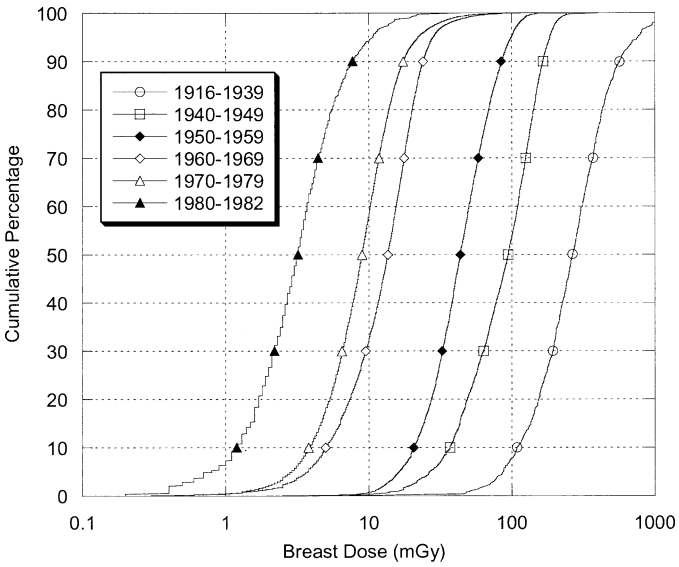

FIG. 8. CDFs of estimated cumulative mean breast dose (mGy) for exposed female technologists by decade first began working (n = 792 for 1916–1929, n = 2,769 for 1940–1949, n = 9,144 for 1950–1959, n = 21,391 for 1960–1969, n = 32,620 for 1970–1979, n = 1,020 for 1980–1982). Note: maximum value (not shown) for period 1916–1939 is 1918 mGy. See Table 8 for summary statistics by decade.

A number of previous suppositions about exposures of medical personnel are supported by this analysis. Specifically, the population average equivalent dose to technologists (represented by badge doses) has apparently declined over the decades of radiologic practice, due in part to technological advances including the use of aluminum filtration in X-ray tubes introduced in the 1940s to reduce patient dose (*39*), the introduction of fluoroscopic image intensifiers in the 1950s, and the introduction of rare-earth intensifying screens in the 1960s and 1970s (*40*). Doses during the 1960s and most of the 1970s appeared quite constant, similar to the situation in the United Kingdom, where little variation was found between 1960 and 1965 (*41*). By the mid-1980s, average annual doses appear to be only a very small fraction of those received prior to 1940. Given the limitations of our data, it is not possible to describe that decline as either continuous or smooth. In fact, our present analyses indicate moderately abrupt changes in average dose from one period to the next (see Table 7). The discontinuities may partially be an artifact of reconstruction; however, they may also reflect the technological advances mentioned above. The dosimetry also indicates substantial differences in organ doses that would not otherwise be obvious from film badge measurements alone. Superficial organs and tissues, e.g. thyroid, testes, female breast, and skin of the head and neck region, received, on average, similar estimated cumulative doses, which were among the highest of all organs assessed. More deeply seated organs, e.g. the ovary, lung, and even more so, the red bone marrow, received cumulative doses that were 15% or less than the doses received by the more superficial organs. Thus our efforts to estimate organ doses will almost certainly make estimates of radiogenic cancer risks more accurate than studies relying solely on film badge measurements.

Dosimetry- and Uncertainty-Related Issues

The definition of uncertainty used in this study is the same as in most other dose reconstructions, i.e., a mathe-

TABLE 10
Sources and Treatment of Uncertainty in Present USRT Dosimetry

Uncertainty	Uncertainty accounted for in present dosimetry?
Badge doses	
Representativeness of data from individual publications in pre-1960 period to USRT cohort	Yes
Representativeness of estimated annual median value exposure estimates to USRT cohort (bias)	Yes
Measurement precision of individual badge readings	Yes
Sparse individual measurement data for 1960 through 1976	Partially[a]
Incomplete measurement data for 1977–1984 and error in statistical modeling	Yes
''True'' annual dose for an individual with a reported dose below the *minimum detectable limit*	Partially[b]
An individual's cumulative dose distribution based on individual's estimated annual dose distributions	Partially[c]
Ratio of mean annual dose in hospitals (over all technologists in a given year) to mean annual dose for working in other types of medical facilities (e.g. private physician's office, combination, dental clinic)	No
Procedures to calibrate film badges or other measurement devices prior to 1960 (bias)	No
Conversion of measurements of air exposure (R), where used, to estimate dose equivalent	No
Organ doses	
Apron use for each individual in each year worked	Partially[d]
Shielding effectiveness of protective aprons	No
Homogeneity (spatial) of radiation fields to which technologists were exposed	No
Actual energies to which technologies were exposed; and proportion of total exposure from those energies	No
Accuracy of conversion coefficient for air kerma to organ dose	No
Degree of exposure of skin for various parts of the body resulting from unknown orientation of technologist with respect to radiation source	No

[a] Uncertainty derived from variation of limited cohort data.
[b] In 1960–1976, lognormal CDF assumed and ''most likely'' value selected.
[c] Annual uncertainties propagated by Monte Carlo method; but correlation in successive years taken as a constant, with no uncertainty.
[d] Discrete uncertainty distribution established for apron use, but probability values are taken as constant, rather than uncertain.

matical quantification, usually in the form of probability density functions, to characterize the state of knowledge. Few radioepidemiological studies, however, have characterized uncertainty on an individual level (*36*). Point estimates of dose, the usual exposure metric in epidemiological studies, almost always represent an overstatement of precision. The characterization of uncertainty and the implementation of methods to propagate that uncertainty distinguish this study from all previous ones of medical radiation workers.

Uncertainty about each technologist's cumulative organ doses arises as a result of lack of knowledge of many factors. The primary identified sources of uncertainty are presented in Table 10. Probably the most significant to estimation of badge dose prior to 1977 is the very limited amount of individual cohort monitoring data, followed by lack of knowledge of data related to how radiologic examinations were performed, as well as individual behaviors that would have contributed to each individual's badge dose. With respect to organ dose, the most significant uncertainties are the possible lack of homogeneity of the radiation fields, the unknown energies of radiations to which workers were exposed, and lack of complete and accurate information on the use of protective devices (e.g. aprons).

One uncertain parameter mentioned in Table 10 is the energy of the radiation to which technologists were exposed. We have considered the possibility of systematic and random error in the organ dose coefficients as a consequence of uncertainty in the energy of the radiation to which we believe technologists were most likely exposed. Technologists would have been exposed primarily to scattered radiation from diagnostic procedures (e.g. single- or multi-film X rays, fluoroscopy) or from the administration of radioisotopes for therapeutic purposes. Exposures from radioisotopes are potentially the most difficult to assess in that dramatic differences in dose are possible depending on how the isotopes were handled and administered.

With respect to Brehmstrahlung radiation emitted from diagnostic X-ray machines, literature indicates that the peak potentials were frequently about 90 to 120 kVp and infrequently below 70 kVp. Hence our assumptions of peak intensities in the X-ray spectrum near 35 keV would be valid for many radiologic examinations. Our assumption concerning the predominant energy of exposure ($\sim$35 keV) from diagnostic radiologic procedures seem to agree well with findings from an occupational exposure study carried out in China in which 608 X-ray machines manufactured from the 1930s through the 1980s were measured for various exposure-related characteristics (*8*). In that effort, the Chinese investigators found that the peak energy was typically at 34 keV. Peak voltages would have been greater for therapeutic applications, but technologists normally would not have been in treatment rooms during those exposures. For circumstances in which higher peak voltages were used, we may have underestimated the organ dose factors for deep-seated organs.

When certain radioisotopes were the sources of exposure, γ rays would have been more energetic than the assumed

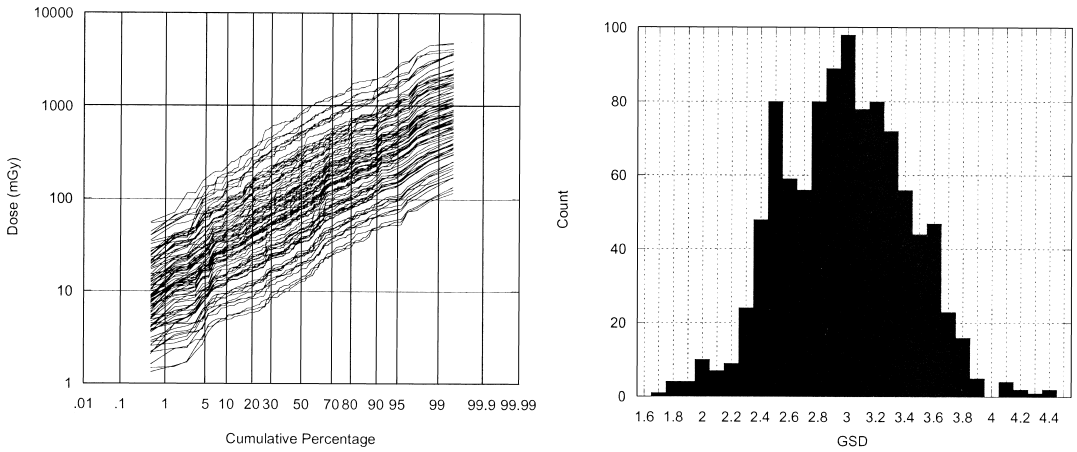

FIG. 9. Left panel: CDFs of cumulative breast doses (mGy) for 100 representative female radiologic technologists (shown as log-probability plots). Each line fits the generated cumulative doses from 100 trials for an individual and is a representation of the uncertainty on the true cumulative breast dose for that technologist. Average GSD is 3.0. Right panel: Histogram of GSDs of cumulative breast doses from representative sample of 1,000 female technologists. Group of 100 shown in left panel is included in histogram.

energy of X rays and would have resulted in underestimated dose factors. However, radioisotopes were generally point sources and would have resulted primarily in high exposures to the hands of technologists.

Though all film badge measurements were uncertain due to measurement imprecision, occasionally film badge readings were reported that appeared unreasonably high and hence were particularly uncertain. The reasons for such readings varied. For example, the Public Health Service, as part of their film badge program in 1967, investigated the causes of unexpectedly high badge readings (*42*), i.e., those that exceeded 3 mSv in a single month. Fourteen badge doses from the approximately 1700 badged individuals in 183 installations exceeded the investigation level; nine of the 14 could not be explained. Reasons for some exceeding the limit included (1) a deliberate exposure to check on the measurement reliability, (2) the badge was worn during an X-ray examination of themselves, (3) the badge was inadvertently left in a diagnostic X-ray room, and (4) the badge was worn for an excessive length of time before processing. Those findings, while based on small numbers, provide a variety of reasons why unexpectedly high doses are sometimes registered. On the other hand, experience at Landauer, Inc. suggests that high film badge readings were usually due to improper mounting of the film in its holder.

Distinctions should be noted between (1) the variation of point estimates of cumulative doses among individuals within periods, (2), the uncertainty in the total or cumulative organ dose for each individual, and (3) the variation of uncertainties among individuals. Figures 8 and 9 in particular illustrate these concepts. Figure 8 shows the population distribution and hence the variation of the mean cumulative breast doses among cohort members within periods. The variations of cumulative mean doses among periods were similar, as can be noted from the similar-shaped CDFs in Fig. 8, even though the population average dose decreased considerably over time. Figure 9 illustrates both the uncertainty of the cumulative dose for 100 representative technologists and the variation of those uncertainties. Each continuous line of Fig. 9 (left panel) represents a single set of plausible cumulative doses for one individual. Note that the simulated data for each cohort member are close to lognormal, as is evident by each line being close to straight on the log-probability plot. Many of the individual technologists' uncertainty distributions have similar slopes indicating they have near identical GSDs or nearly the same degree of relative uncertainty, though a few have shallower slopes (smaller GSDs) and some have steeper slopes (larger GSDs). The few with steeper slopes represent individuals for which the true cumulative dose is more uncertain. The right panel of Fig. 9 shows a histogram of GSDs on cumulative breast dose among 1,000 representative female technologists. The group selected for this illustration had moderately long working careers, averaging 17.7 years, and 95% began working before 1960. The mean GSD for cumulative breast dose among the 1,000 selected technologists, from which the 100 displayed in the left panel of Fig. 9 were selected, was 3.0. Individual GSDs varied from 1.7 to 4.4. If temporal correlations were not included, the mean GSD was considerably less, about 1.6.

Finally, we note that the use of the uncertainty distributions in any dose–response analysis requires care and consideration of the source and nature of the uncertainties. See the paper by Schafer and Gilbert (*43*) in this issue for further discussion.

Comparison of Estimated Doses to Literature

1. U.S. studies

It is useful to compare our findings with other data reported in the U.S. literature, although it is likely that such

data may not be completely independent from our own because of the large size of our national cohort, which included workers entering as early as 1916 or as late as the early 1980s. A Public Health Service (PHS) study conducted in 1967 described 1689 individuals included in the PHS film badge program (*42*). A subset of PHS employees who were monitored with film badges were X-ray technicians among whom 76.8% had estimated doses of 0–0.09 mSv month^{-1} (76.8%), 0.1–0.5 mSv month^{-1} (16.7%), 0.5–1.0 mSv month^{-1} (4.5%), 1–2 mSv month^{-1} (1.4%), and 2–4 mSv month^{-1} (0.7%). Similar to the badge readings from members of our cohort, a higher proportion of the X-ray technicians working in the PHS hospitals had estimated radiation exposures in the higher dose categories compared to all PHS X-ray technicians grouped together. Moreover, the average of the above dose categories was 1.9 mSv year^{-1}, the same as our estimate in 1967 (Table 7) for a combination of hospitals and physicians' offices.

Limited occupational dose data has been reported for the U.S. military for the years of 1969 and 1970 (*44*). Medical X-ray workers, regardless of the branch of the military, received similar doses in those 2 years: Army and Air Force ''medical'' workers and Air Force ''medical nuclide'' workers received on average about 1 mSv, Navy ''medical'' workers received slightly less, about 0.83 mSv, while Air Force ''dental X-ray workers'' received 0.77 mSv. In contrast, the U.S. EPA (*44*) reported that medical X-ray workers overall (about 204,000 workers) received in 1969, about 630 man-Sv (63,000 man-rem), an average annual individual dose of 3.1 mSv. It is unclear why the annual doses in the military were lower than in civilian institutions; possible explanations are more stringent protective measures and/or smaller workloads for individual technologists. Both the EPA and military data were consistent with our analysis that indicated a median and mean annual equivalent dose of 2.2 and 3.6 mSv, respectively (95% CI of 0.3 to 16 mSv).

Estimates of trends of occupational exposure in the U.S. were published by Kumazawa *et al.* (*28*) for the years 1960–1985. For example, they reported on doses in the ''medicine'' subcategory, using a simple temporal model to approximate dose. The model could be described by an annual mean dose of 3.1 mSv (310 mrem) in 1960 and a linear decrease such that the 1960 mean dose was halved in magnitude each span of 14 years thereafter. Though our analysis (Table 7) did not indicate an exponential transition as described by Kumazawa *et al.* (*28*), the doses they estimated were within the central region of our uncertainty distributions shown in Table 7.

In addition, Kumazawa *et al.* (*28*) found differences between doses received by technologists in hospitals and physicians' offices between 1960 and 1975. That observation was later verified in data obtained for this study from Landauer, Inc. In general, annual doses for medical X-ray workers in private medical clinics were lower than for their counterparts in hospitals, with the difference presumably due to a lower workload in private clinics. According to Kumazawa *et al.* (*28*), annual doses in private practice clinics were on average about 70 to 80% of the dose received by hospital workers. Furthermore, in 1960, X-ray workers in dentistry received about 40% of the annual dose received by hospital X-ray workers. By 1985, dental X-ray workers received on average only about 13% of the dose received by hospital X-ray workers.

2. International studies

Our dose estimates can also be compared to estimates in studies conducted in Canada (*23*), China (*7, 8*) and Japan (*5*). For most years, the estimates of average dose in those studies are comparable to our findings for the U.S., that is, within the same order of magnitude. However, we should not expect average doses in different countries to be the same, because it is not possible to know all the differences in technology, as well as how radiologic practices were implemented in the different countries. More importantly, it should be recognized that the average dose in each of the studies is highly uncertain and that reported point estimates in international studies are within the uncertainty ranges we have derived.

In Canada, some 73,000 medical radiation workers, about 60% of which were female, have been studied (*23*). That cohort worked between 1951 and 1988. Dose estimates were assembled from monitoring records carried out by the National Dosimetry Service and Atomic Energy of Canada Limited. No reconstruction of doses was undertaken for years prior to 1951, when personnel monitoring began. Similar to that in the U.S., monitoring frequency was weekly before 1955 and in transition to bi-weekly measurements between 1955 and 1963. No model of dose as a function of time, job description, etc. was reported since doses were based primarily on measurements. The average dose to the Canadian cohort was 6.4 mSv, though no organ doses were specified. Comparing to Table 8 for the USRT cohort shows that the mean dose equivalent in the Canadian study was smaller than doses for superficial organs and tissues in our study (e.g. breast, testes and thyroid), but close in magnitude to the mean dose to a deep-seated organ such as the ovary.

In Japan, a cohort of about 12,000 radiologic technologists has been studied. Similar to the situation in the U.S., no dose records were available prior to 1960, about the time that personnel monitoring was introduced in Japan. The study of Japanese X-ray technologists used a parametric equation to predict annual dose based on year of work, type of facility (university hospital, general hospital, public health center), and a categorical variable describing the quality of protective measures (good, ordinary, poor). Parameter values were derived from regression analyses of available dose data. The predictive model for dose used was $\text{Dose} = \alpha \exp[-\beta(\text{year} - 1925)]$. Values of α ranged from 0.06 (good protective measures) to 0.36 (poor protec-

tion), and values of β ranged from 0.05 to 0.09 and depended on facility type. The estimated annual dose in the Japanese study agreed closely with our estimates in the early- to mid-1950s and after 1980. During the intervening years (i.e. 1955–1980), the Japanese study predicted an exponential decline, considerably different than the uniform values within decades that we assessed (Table 7).

A study in China of 27,000 medical diagnostic X-ray workers (*7, 8*) had more severe limitations compared to other studies because dosimetry records were not available prior to 1990. The Chinese study relied on ''simulation'' of 608 X-ray machines manufactured from the 1930s through the 1980s and 1632 workplaces; however, it is unclear what measurements were actually made on the X-ray machines. According to data collected from this study, average skin dose was reported to be 182 mGy per year prior to 1950, decreasing to about 35 mGy per year during the early 1960s and to about 4 mGy per year in the early 1980s. The Chinese study predicted a dose equivalent (badge dose) before 1960 of about two-thirds of the mean estimate of our study but agreed very closely after 1970.

CONCLUDING REMARKS

The dosimetric findings presented here for the USRT cohort are more detailed but are generally consistent with other published studies of radiologic personnel, including cohorts in other countries. That general consistency is reassuring because similar radiologic technologies have been available worldwide and thus similar average annual doses would be expected.

We are continuing to refine the current dosimetry reconstruction with a goal to reduce the variance in each cohort subject's annual dose uncertainty distribution. To that end, we are acquiring more cohort-specific individual monitoring data from the military services and from sentinel hospitals that employed large numbers of technologists in the USRT cohort. In addition, an imminent survey of all USRT cohort members will provide detailed information on procedures performed, behavior and protective measures used by decade and by job. Noting that the current uncertainty distributions are based on the variability of dose data within a decade, we hope to reduce the uncertainties by identifying individuals with the highest and lowest exposures. The overall uncertainty distribution can then be partitioned at the extremes, and low- and high-end exposure individuals can be assigned to those modified narrower densities.

Given the size of the USRT cohort, the number of specific organs/tissues considered, the development of year-by-year uncertainty distributions, and the estimation of multiple realizations of organ doses, this study is the most comprehensive dose reconstruction to date for radiology personnel.

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