STATUS REPORT ON ESTIMATING HISTORICAL RADIATION DOSES TO A COHORT OF U.S. RADIOLOGIC TECHNOLOGISTS

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Abstract: Data have been collected and physical and statistical models constructed to estimate unknown occupational radiation doses to 90,000 members of the U.S. Radiological Technologists cohort who responded to a questionnaire during the mid-1980s on occupational practices. Since the availability of radiation dose data differed by calendar time period, different models were developed for purposes of dose reconstruction during the years before 1960, 1960-1976, and 1977-1984. The dosimetry 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 complete 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 realizations of cumulative organ doses for preliminary cancer risk analyses. Estimates of organ dose (mGy) averaged over the cohort are presented here for purposes of summarizing the present (June 2004) findings: 24 mGy to female breast (n=67,736), 6.6 mGy to ovary (n=67,736), 40 mGy to testes (n=20,008), 11 mGy to lung (n=87,742), 62 mGy to thyroid (n=87,744), 3 mGy to bone marrow (n=87,652), 33 mGy to skin on the trunk of the body (n=87,744), and 79 mGy to skin on the head, neck, and arms (n=87,744). Maximum estimated doses where about 60 times the mean value for most organ/tissue sites. 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. Extrapolation of high doses from Atomic Bomb survivor studies and medically irradiated patients, as well as studies of non-medical nuclear workers have been the primary sources for understanding the risks from chronic low-level radiation exposure.

The U.S. Radiologic Technologists (USRT) cohort, assembled in the early 1980s using records of the American Registry of Radiologic Technologists, includes 146,000 technologists certified for at least two years during the period 1926-82 *(1)*. This unique cohort is 73% female, with a current median age of

about 52 years. Presently, the National Cancer Institute is conducting a retrospective follow-up and assessment of mortality and radiogenic cancer risks among this group *(2)*.

Cohort members first worked as radiologic technologists as long ago as 1916 or as recently as the early 1980s. As explicitly shown later, the number of years worked and the decade in which a technologist worked greatly influenced the cumulative occupational dose received. Technologists who first began working prior to 1940 (n=1,032), during 1940-49 (n=4,236), during 1950-59 (n=12,096), during 1960-69 (n=26,799), during 1970-79 (n=42,358), and during 1980-84 (n=1,252) had worked on average, 25, 22, 17, 14, 9, and 4 years, respectively, by the mid-1980s when the 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.

Three aspects of this work 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 used, in part, to derive individual cumulative doses. Second, detailed individual work history and practices information was obtained from questionnaires completed by a large fraction of eligible cohort members, and used to adjust film badge measurements. The key work practices information obtained from questionnaires included: protective apron usage, 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, including follow-up investigations of radiologic technologists in the U.S. Army *(3,4)*, Chinese diagnostic x-ray workers *(3,7,8,5,6 ,7)*, Danish radiotherapy workers *(4)*, Japanese radiologic technologists *(5,8,)*, and Canadian radiation workers *(9)*. 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 radiological technologists separately from other radiation workers.

The impetus for the detailed dosimetry described here is its value to support mortality and cancer risk analyses from data collected on the USRT cohort. Medical personnel occupationally exposed to ionizing radiation are one of the few groups available for such study.

METHODS

Overview and Objectives

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 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), often called an uncertainty distribution, that represents the range and likelihoods of plausible values for the true annual dose.

Because the availability and quality of badge dose data differed by time period, we developed different dose estimation methods for three specific time periods: prior to 1960, 1960 through 1976, and 1977 through 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 time 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: Brief Summary of Methods

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

Table 1. Badge dose estimation by time 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	11,498
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.	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.
Distributions developed for 3 sub-periods (<1940, 1940-1949, 1950-1959).		

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

Pre-1960. The 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. We identified eleven 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.

Badge dose distributions were developed for 10-year periods primarily because the sparse literature data did not allow us to discern changes in dose over shorter periods. The period before 1940 is particularly problematic as 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 distributions, we first evaluated the film badge data presented in the eleven 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) were often not explicitly stated. A set of film badge readings from

each publication was derived, taking into account the time interval over which monitoring was conducted, and the monitoring frequency.

The simplest approach would have been to pool all the badge measurements, by decade; however, this assumes that the proportion of badges from each publication is in the same proportion as the cohort For example, the data from readings at Massachusetts General Hospital, represent approximately 60% of the 1940-1949 literature badge doses; but this is an academic hospital, with ostensibly the most progressive practices, and hence, worker exposure there was not likely representative of 60% of the entire cohort. Consequently, each publication was assigned a weighting factor, with uncertainty (the uncertainty density was taken as a uniform density).

A Monte Carlo simulation was performed, sampling the weights for each publication and generating global densities for each trial. This was repeated 30 times for a specified number of trials. The procedure was repeated thirty times and the means and variances averaged over the 30 trials.

1960-1977. In this time 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) from employers. The badge readings represented about 560 individuals, though they were treated as independent measurements and pooled to determine the average dose within the time period.For 1960 through 1977, cohort, we restricted the badge doses to the approximate 500 badge readings taken on the outside of the apron as reported by cohort members on the baseline questionnaire. This was to 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 technologist's apron. The data indicated nearly the same average annual dose for each year; therefore, we used a constant value to represent the average badge dose for each year across the entire time period.

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, complexities arose because of zero-valued annual dose readings, and very low annual doses that included monthly or more frequent minimal detectable limits.

Therefore, 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. The likelihood function has terms of CDF(*D*), where we assume the true dose is less than or equal to *D*.

The likelihood function (eq. 1) is then:

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

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, $i > k$. The likelihood function (eq. 1) was maximized to obtained estimates for the overall mean and variance of a dose uncertainty distribution for a single year. This density was applied for every year during the period 1960-1976.

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. For 1977-1994, approximately 350,000 annual badge readings were obtained for cohort members from the computerized records of Landauer. 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 :

$$\ln(Dose_j) = \$_1 X_{j1} + \$_2 X_{j2} + \ldots + \$_k Xj_k + \ , j, \qquad (2)$$

where the $\$_i$ (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 **,** denote a covariance matrix structure; then **y = X$ + ,.**

Predictor 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); the technologist's sex and age in 1984, when the baseline questionnaire was administered. 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.

To establish an uncertainty distribution: 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 density was derived from the modeling error, in turn, considered to be the sum of two errors: a propagation of errors term and the residual error, yielding a GSD of 2.32

Estimation of Organ Doses

Organ doses were estimated from measured or estimated "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 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..

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) *(10)*: 1) the organ absorbed dose per unit of air kerma free-in-air (Gy per Gy); and 2) the personal dose equivalent per unit of air kerma free-in air (Sv per Gy). Table 2 below provides the dose factors used for organ dose computation, based on film badge readings. 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 are used.

Table 5. Tissue and organ dose coefficients in Gy per Sv (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)	$\frac{D_T}{K_a} / \frac{H_p(d)}{K_a}$ [Gy/Sv]	D_T/K_a (Gy/Gy)	$H_p(d)/K_a$ (Sv/Gy)	$\frac{D_T}{K_a} / \frac{H_p(d)}{K_a}$ [Gy/Sv]	$\frac{D_T}{K_a} / \frac{H_p(d)}{K_a}$ [Gy/Sv]
red bone	10	0.0697	1.112	0.063	0.211	1.49	0.14	0.10

marrow								
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 x 0.654[a]] = 1.31	1.230	~1.1[b]	[2 x 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 averages the energy fluence over the entire skin. In this situation, the back of the body is assumed not be to 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.

Accounting for effects of protective apron usage. 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. The data collected from the cohort self-administered questionnaire allowed us to formulate a discrete-valued probability density function describing the likelihood of protection for each individual, for each year worked.. The density can be defined for each year by probabilities of three mutually exclusive events: 1) did not wear an apron; 2) wore an apron and a badge outside of apron; 3) wore an apron and a badge under apron. Let $P_{NoA,}$ P_{AO}, and P_{AU} denote the probabilities for those respective events. Thus, the discrete 'probability-of-protection' function, $P_{Protection}$, can be described as:

$$P_{Protection} = \begin{cases} P_{NoA} & \text{(probability of no apron)} \\ P_{AO} & \text{(probability of badge outside the apron)} \\ P_{AU} & \text{(probability of badge under the apron)} \end{cases} \qquad (3)$$

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Apron attenuation describes the reduction in dose received while wearing a protective lead apron. Typical thicknesses for lead aprons have been 0.25 mm and 0.5 mm Pb equivalent. For x-ray beams of 70 kVp, 100 kVp, 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 *(11,12)*. In this study, we assumed an 80% reduction in exposure beneath the apron (no more than 20% transmission) to account for three possibilities: 1) some aprons worn were thinner than 0.5 mm Pb, 2) scattered radiation results in some exposure to parts of the body unshielded by the apron, and 3) 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. *(13)* who studied exposures of personnel performing fluoroscopy, however, in many circumstances, aprons would be more protective than estimated.

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 2), the probability of protection density 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:

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

$$\text{Organ dose (mGy/yr)} = BD_{m,sim} \times DF_o \times [P_{NoA} + AA \times P_{AO} + P_{AU}] \quad (4)$$

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

$$\text{Organ dose (mGy/yr)} = BD_{m,sim} \times DF_o \times [P_{NoA} + P_{AO} + (1/AA) \times P_{AU}]. \quad (5)$$

where,

$BD_{m,sim}$ = badge dose (either measured or simulated)

DF_o = dose factor for a specific organ,

P_{NoA}, P_{AO}, and P_{AU} = the probabilities for not wearing an apron, wearing an apron with the badge outside, and wearing an apron with the badge underneath, respectively,

AA = apron attenuation factor, taken as .4 (assuming "usually wore an apron" from questionnaire means 75% of the time).

Uncertainty and Dose Estimation: Simulation, Correction for Bias, and Correlation. The dosimetry for each individual, as noted previously, is a year-by-year lognormal density of badge dose (and associated organ doses). To obtain realizations of cumulative dose for each individual, Monte Carlo simulation was used. In addition, because there is a potential for bias in the means of each lognormal density, and because an individual's yearly dose is correlated with the subsequent year's dose, we introduce a correction for bias in the mean, as well as a temporal correlation. The temporal correlation was based on the rank correlation method by Iman and Conover. Given space limitations, these issues are not covered here, but were incorporated in the dosimetry reconstruction.

FINDINGS

For the 87,744 technologists who worked for at least one 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. The Tables 3 , 4 and 5 below summarize some of the basic findings to-date.

Table 3 presents the mean, median and GSD (of uncertainty distribution) of annual estimated badge doses (mSv) for the 87,744 exposed technologists by time period and type of facility. 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 1960-1976 period.

Table3. 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 time periods is based on variability of model predictions among cohort members working during the specific time period. If subject had a film-badge measurement, the GSD is assumed to be 1.2.

Table 4 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 time period 1916-1984. 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 values 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 receive 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 (CV) for most organs/tissues were similar (~1.7 to 2.0).

Table 4. Summary statistics on estimated cumulative mean organ doses (mGy) over all years worked (1916-1984); summary statistics are for non-zero values only

	Female breast dose (mGy)	Ovary dose (mGy)	Testes 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	2300	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

Table 5 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 1916-39 and 1940-49, the estimated cumulative dose to the breast fell from 320 mSv

on average to 98 mSv on average; thereafter the mean dose declined by 50% or more between the years 1940-49 and 1950-59 and between 1950-59 and 1960-69. The declines in mean average dose were smaller between 1960-69 and 1970-79 and between 1970-79 and 1980-89.

Table 5. 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

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. 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, to date, this study is the most comprehensive dose reconstruction for radiologic personnel.

A number of previous suppositions about exposures of medical personnel are supported by this analysis. In particular, the population average equivalent dose to technologists (represented by badge doses) has declined over the decades of radiologic practice. Doses during the 1960's and most of the 1970's were quite constant, however, similar to the situation in the United Kingdom where there was little variation found between 1960 and 1965 *(14)*. By the mid-1980s, average annual doses appear to be only a very small fraction of those received prior to 1940..

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 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.

We are continuing to refine the dosimetry. One aim is to reduce the uncertainty in each individual's annual dose density, by partitioning those with either "most likely" extremely high or "most likely" extremely low densities. Information from and additional cohort survey (in mid 2004) will provide

detailed information on types and frequency of procedures performed, as well as detailed protection practices, by year. Additionally, 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.

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