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Dosimetry for the study of medical radiation workers with a focus on the mean absorbed dose to the lung, brain and other organs

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Abstract

Background: The reconstruction of lifetime radiation doses for medical workers presents special challenges not commonly encountered for the other worker cohorts comprising the Million Worker Study.

Methods: The selection of approximately 175,000 medical radiation workers relies on using estimates of lifetime and annual personal monitoring results collected since 1977. Approaches have been created to adjust the monitoring results so that mean organ absorbed doses can be estimated.

Results: Changes in medical technology and practices have altered the radiation exposure environments to which a worker may have been exposed during their career. Other temporal factors include shifts in regulatory requirements that influenced the conduct of radiation monitoring and the changes in the measured dose quantities.

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Disclosure statement

The author's report no conflicts of interest. RCY was employed by Landauer Inc. who provided the database being used by the NCRP for the Million Person Study. CNP is currently employed by Landauer, Inc. The work in preparing this paper is entirely voluntary, entails no financial implications and only involves the scientific interpretation and application of the radiation measurement data acquired many years ago by Landauer.

Conclusions: The use of leaded aprons during exposure to lower energy X rays encountered in fluoroscopically based radiology adds complexity to account for the shielding of the organs located in the torso when dosimeters were worn over leaded aprons. Estimating doses to unshielded tissues such as the brain and lens of the eye become less challenging when dosimeters are worn at the collar above the apron. The absence of leaded aprons in the higher energy photon settings lead to a more straightforward process of relating dosimeter results to mean organ doses.

Keywords

Dosimetry; epidemiology; personal monitoring

Introduction

The Million Worker Study (MWS) seeks to combine the radiation dose and mortality experiences from several occupational groups in an effort to better understand the incidence of cancer induction to people occupationally exposed to low levels of radiation for many years. This study is being conducted under the direction of the National Council on Radiation Protection. Medical radiation workers represent one of the occupational groups that includes large numbers of women from which sex-related radiation effects can be potentially identified. Of particular concern is the unexplained difference in the radiation-related incidence of lung cancer between the male and female survivors of the Japanese atomic bombings with females having an approximate three times greater risk of contracting the disease. This difference has caught the attention of the National Aeronautical Space Administration (NASA) as it addresses the risks from space radiations to male and female astronauts making space flights to Mars (Boice 2017, 2019; Boice et al. 2018).

The National Council on Radiation Protection and Measurements (NCRP) expects to publish general guidance directed at the MWS for estimating the mean absorbed dose for the primary and secondary organs considered by the International Commission on Radiological Protection (ICRP) to present the risks of stochastic diseases (ICRP 2010). A summary of the contents of this report was prepared by Bouville et al (2015). In 2018, the NCRP created Scientific Committee 6–11 to draft specific guidance for reconstructing the mean absorbed dose to the lung and selected other organs using personal monitoring results for the medical radiation worker cohort of the MWS. The Committee expects to complete its work in late 2019. The following describes the major issues and their intended resolutions identified by the Committee. These issues include the methods to assimilate decades of dosimetry data pertaining to approximately 175,000 workers who were collectively employed by thousands of hospitals, clinics, and private practices; and for whom little direct knowledge exists about the specific conditions to which a particular person might have been exposed. The conditions of exposure are critical for the dose reconstruction process in which dosimeter results must be converted into estimates of the personal dose equivalent, $H_P(10)$, followed by the conversion of $H_P(10)$ estimates into estimates of mean absorbed dose to an organ or tissue.

The effort and resources required for dose reconstruction depend largely on the availability and form of the dosimetry records. For certain groups of workers, dose information can be

retrieved from national databases maintained by the US Nuclear Regulatory Commission and the US Department of Energy created as part of their national regulatory responsibilities. The Federal databases aid the effort to collect doses a particular person may have incurred at different institutions regulated by these government entities. The uses of X rays are regulated individually by each State, and thus this regulatory structure has precluded the formation of a nationwide database of doses received by medical workers. In lieu of a nationally oriented database, the MWS has had to rely on an electronic records database developed by Landauer, Inc., a supplier of personal monitoring services. The firm's history and its sizeable market share pertaining to hospitals and medical clinics have enabled it to create a nationally scoped dosimetry records repository.

Methods and discussion of key topics under consideration for dose reconstruction

Selection of the medical radiation worker cohort

An initial medical radiation worker cohort is to be assembled using very preliminary estimates of lifetime doses (quasi-lifetime doses) contained in the Landauer database. All workers having lifetime doses equal to or greater than 50 mSv are to be automatically selected. Adding to this group will be random selections of 50% of those having lifetime doses between 10 and 50 mSv and 2% of those workers having a lifetime dose less than 10 mSv. As noted below, there are large uncertainties regarding these lifetime dose estimates. The cohort is expected to total approximately 175,000 people selected from an eligible population of 1.71 million medical workers.

The source of dosimetry information

The basic information used to select the medical radiation worker cohort and reconstruct both annual and lifetime mean organ absorbed doses originates from a special digital database created by Landauer, Inc. in the mid-1980s following an informal agreement to assist with an epidemiology study of registered radiation technologists being conducted by the Radiation Epidemiology Branch of the National Cancer Institute (Boice et al. 1992; Simon et al. 2006). The database contains annual doses for 1977 and later years; although annual doses for the years 1960 through 1976 can be obtained through manual examination of microfilm copies of dosimetry reports for many workers. Missing from the epidemiological database are the individual dosimeter results that when summed create the stored annual and quasi-lifetime doses. Individual dosimeter results communicated to the client via a Dosimetry Report indicate the monitoring period (e.g. weekly, monthly, quarterly, etc.), the quantitative dose values with indications of the radiation type and energies detected, and the quarterly, annual and lifetime to date dose totals. These reports have been archived as images, not as digital data. The archived report images remain available for quality control checks and to verify assignments to workers to radiation exposure scenarios as the dose reconstruction process dictates.

Through an enrollment process, each institution assigns their radiation workers to one or more account numbers, hereinafter called accounts. Within a specific account, each worker is given a numerical identifier called a participant number. The participant number is only

unique to a worker within one account number. Dosimeter results and their totals are attached to each participant at the account level. Each combination of account number and participant number represents a distinct entity for which annual and quasi-lifetime dose values are stored. The term quasi-lifetime dose refers to the fact that the lifetime dose in the database only refers to the total dose received by a worker as an enrollee in an account and does not necessarily include dose history from other accounts. Linking a worker across accounts requires the use of personal identifiers (name, birthdate, and government provided identification numbers) provided during the enrollment process. However, the provision of personal identifiers is and was not mandatory. Workers with no personal identifier were ineligible for selection into the study cohort. Those workers that could be tracked across multiple accounts may have some lifetime dose histories from prior employers counted multiple times thus artificially increasing their apparent lifetime dose. Fortunately, there exist within the database information that can help resolve these errant conditions during dose reconstruction. Those medical workers routinely receiving dose with long careers at one institution will more likely have more complete dose histories because few instances will exist of having to combine dose from multiple accounts.

Workers could be assigned to a client-defined group called a series or subaccount. The series code often reflects a department or specialty within the hospital and is useful for understanding the radiations to which workers in that series were exposed. Frequently the codes were abbreviations of departments such as RAD for radiology, NUC for nuclear medicine and CAR for cardiology.

Personal dosimetry considerations

The annual and lifetime doses in the database represent the summation of a series of personal monitoring measurements acquired over various monitoring periods. Depending on the year and dosimeter technology; employers issued personal radiation monitors to workers primarily on a weekly, monthly, or quarterly frequency; although some institutions used biweekly and bimonthly exchange periods as well. The monitoring frequency dictates the number of measurements summed to calculate the annual dose totals and thereby affects the overall uncertainty in the annual dose value; however, the medical worker dosimetry database does not indicate monitoring frequency. Monitoring frequency must be inferred from the year of the annual dose value and the predominant monitoring frequencies selected by Landauer's clients at that time. Dosimetry results from the 1950s were predominantly from weekly measurements as then recommended dose limits were expressed in terms of weekly exposures. Later years witnessed a shift from more frequent to less frequent dosimeter exchange periods as the expression of dose limits in terms of 13-week periods enabled monthly and quarterly monitoring. In addition to quarterly dose limits, a lifetime dose limit was also adopted by regulators. The 1960s contained a mix of weekly and monthly monitoring with weekly being more prevalent in the early part of the decade and monthly becoming more widely used by the end of the decade. Landauer's adoption of the more stable thermoluminescence dosimetry (TLD) technology in 1974 allowed the introduction of quarterly monitoring but the use of this frequency never overtook monthly monitoring. Quarterly monitoring did not provide radiation safety staff timely information to prevent highly exposed workers from receiving doses that exceeded the quarterly regulatory

limits in force during the period from the early 1960s through the mid-1990s. Consequently, quarterly monitoring was mostly selected for the lesser exposed worker and is expected to be less prevalent among the selected medical radiation worker cohort. As the cohort selection method preferentially includes high dose workers, the Committee has assumed that 100% of annual doses received after 1970 to be from monthly monitoring.

Monitoring frequency also influences the amount of dose that could not be measured due to the dosimetry system's lower limit of detection or minimum reportable dose. Often referred to as 'missed dose', doses that do not exceed the detection limit or minimum reportable dose are given a value of zero for reporting purposes. Epidemiologists have attempted to account for the missed dose by adding an estimate of the dose that could have been received but not detected based on a presumed dose value intermediate between zero and the minimum reportable value. Prior to 1998, the minimum reportable value was 0.1 mSv (10 mrem as reported to the client) irrespective of the quantity being reported, for example, exposure, restricted dose equivalent index, personal dose equivalent. The minimum reportable dose became 0.01 mSv with the introduction of optically stimulated luminescent dosimetry (OSL) in 1998. By 2002, Landauer had converted all of its film and TLD users to OSL thus reducing the amount of dose possibly undetected. For the highly exposed members of the medical worker cohort, the missed dose does not likely contribute a significant amount of unrecorded dose because most dosimeters yielded measurements above the minimum reportable value. However, those workers having lifetime doses of 10 mSv or less probably had many instances of dosimeter results being less than the reportable threshold so that over a career of 35 years or more, the missed dose could represent a meaningful percentage of the worker's total dose. The Committee has decided that for the lowest exposed segment of the cohort, an annual value of 0.4 mSv be assumed for each annual dose record having no measurements above the minimum reportable value. This is based on an estimated median monthly dose of approximately 0.035 mSv for those receiving less than 0.1 mSv per month as assessed from recent OSL results.

An advantage of the Landauer database is the consistent approach to dosimetry practiced over time. While multiple dosimeter technologies (e.g. film, thermoluminescent dosimeters, and optically stimulated dosimeters) and dosimeter models were employed by Landauer at various times from the period 1954 through the present, the results all link back to common calibration and data analysis philosophies that kept dosimeter measurement performance relatively consistent and lessens the uncertainty arising from combining results originating from different dosimeter models compared to combining dosimeter results originating from different dosimetry services or laboratories. A discussion of measurement uncertainties can be found in NCRP Report 158 (NCRP 2007).

The quantity of each annual dose value is the one defined for regulatory compliance at that time: *exposure* (X) for years before 1985; restricted dose equivalent index (DEI) for years 1985 through 1994; personal dose equivalent ($H_P(10)$ also called deep dose equivalent) for the years after 1994 and the effective dose equivalent (H_E) for years after about 1998. Since 1998, the annual doses can be either $H_P(10)$ or H_E depending on whether the worker was involved with fluoroscopic procedures. With the exception of the personal dose equivalent (and to some extent the restricted dose equivalent index), values of *exposure* and effective

dose equivalent must be converted to the personal dose equivalent in order to use the conversion factors presented in Figures 2–8. Prior to 1985, all Landauer dosimeter results reflect the quantity, *exposure*, at the surface of the body and this was considered equivalent to the dose equivalent to tissue. Using basic radiation mass energy absorption coefficients it is a relatively simple process of converting values of *exposure* to $H_P(10)$. The roentgen value measured from the dosimeter approximates $H_p(10)$, expressed here in rem for the purpose of the comparison, to within 5% for energies above 150 keV and within a maximum of 15% for energies between 50 and 150 keV.

The commencement in 1985 of dosimeter performance testing in accordance with ANSI N13.11-1983 (ANSI 1983) and the regulatory inducement for dosimetry services to become accredited by the National Voluntary Laboratory Accreditation Program caused Landauer to modify its dosimeter analysis formulas to assess the *restricted* dose equivalent index. Based on the dose equivalent index defined by the International Commission on Radiation Units and Measurements (ICRU 1971), the restricted dose equivalent index is the dose at 10 mm depth in a spherical phantom of tissue equivalent material along the central axis of the radiation beam while the dose equivalent index is the maximum dose at any depth in the sphere along the central axis. The latter quantity suffered from practical problems such as non-additivity when different radiation conditions caused maximum doses at different depths (Johns 1980). A 1995 revision to dosimeter performance testing altered the dose quantity to the deep dose equivalent or the dose at 10 mm depth along the central axis in a slab phantom of tissue equivalent material. The deep dose equivalent is functionally identical to the personal dose equivalent, $H_P(10)$ described by the ICRP (1996). The formal definition of the personal dose equivalent is the dose at a point in the body at a depth in soft tissue, not in a slab phantom; however the dose in the slab phantom composed of ICRU four-element, tissue-equivalent material (ICRU 1993) has generally been accepted as an operational surrogate. The slab phantom features more scattered radiation at the 10 mm depth and therefore, the dose in the slab for a given photon fluence or air kerma exceeds that in the sphere by about 10–15% for X rays with energies commonly encountered in diagnostic radiology and only a few percent for the higher energy gamma rays found in nuclear medicine.

In 1977, the ICRP introduced a new radiation protection quantity for use in setting dose limits, evolving in terminology from the effective dose equivalent (H_E) based on one set of tissue weighting factors to the effective dose (E) based on newer tissue weighting factors, (ICRP 1977, 1990, 2007). The quantity in any of its definitions is immeasurable and defined as a formulaic summation of mean organ and tissue absorbed doses adjusted for radiation quality and weighted by the relative risk an organ presents for the development of stochastic health effects. The effective dose equivalent and effective dose are not quantities that exist at a point in the body because organs and tissues are dispersed throughout and a mean absorbed dose in an organ reflects the overall deposition of energy in the entire mass of the organ; meaning that parts of the organ receive more and some parts less than the mean. Personal monitoring has been based on measuring point quantities, one of which is the personal dose equivalent, $H_P(10)$. Federal and State regulatory changes that became effective in the mid-1990s philosophically adopted the effective dose equivalent but equated it to $H_P(10)$ for external irradiation of the body for most exposure situations. Generally, $H_P(10)$

overestimates the effective dose and effective dose equivalent, particularly for areas using X rays for imaging because significant attenuation occurs in the larger organs that contribute most to the stochastic risk and are located at depths in the body much greater than 10 mm (Figure 1). This conservatism becomes excessive when $H_P(10)$ values assessed from dosimeters worn over leaded aprons are assumed to be equal to the effective dose equivalent because most of the organs contributing to stochastic disease risk are located in the torso and thus shielded. To some extent, this overly conservative approach to estimating effective dose has been practically rectified by various proposals to adjust the measured values of $H_P(10)$ as discussed below.

Regulations and regulatory guidance dictate the conduct of personal monitoring. When personal dosimeters are properly used, monitoring relies on the assumption that the same radiation field is incident on the dosimeter and worker at the same time for the same duration. This permits the dose value measured by the dosimeter to be considered the same as that received by the person. Regulations have required dosimeters be located at the highest point of dose on the whole body (Extremities are separately monitored). In most situations when the radiation source is in front of the body and no protective apron is used, it has been acceptable to wear dosimeters on the chest or abdomen. When a protective apron is used, the torso is shielded so that the head becomes the point of highest dose. For practical reasons, dosimeters came to be worn over the apron at the collar; although this has not been a universal practice with some radiation safety officials preferring to have the dosimeters worn under the apron and some electing to require two dosimeters be worn, one under and one over the apron (Brateman 1989; Bushong 1989; NCRP 1989; Simon et al. 2006). Dosimeters worn at the collar over the apron also provide means of assessing dose to the lens of the eye, a tissue with separate regulatory limits.

As noted earlier, a dosimeter located at the collar above a leaded apron provides an inappropriate estimate of the effective dose equivalent. Numerous medical and health physicists have suggested formulas that translate a dosimeter measurement made over the apron or a combination of dosimeter measurements, one made under and one made over the apron into an estimate of effective dose equivalent (Webster 1989; Niklason et al. 1993, NCRP 1995). There has been a continued debate both nationally and internationally as to the preferred approach to monitor medical staff in the fluoroscopy suite; one dosimeter over the apron or two dosimeters, one under and one over the apron; with the ICRP favoring the latter (ICRP 2018). In the late 1990s, State regulatory agencies began to allow doses for medical staff involved with fluoroscopically guided procedures to be reported as the effective dose using the NCRP recommended formulas (NCRP 1995). Equation 1 is the formula recommended for a single dosimeter worn over the apron at the collar and Equation 2 is the formula for two dosimeters, one worn over the apron at the collar and one worn under the apron on the chest.

$$\text{Effective dose equivalent} = 0.3 \times H_P(10)_{over} \quad (1)$$

$$\text{Effective dose equivalent} = 0.04 \times H_P(10)_{over} + 1.5 \times H_P(10)_{under} \quad (2)$$

$H_P(10)_{over}$ is from the dosimeter located over the apron while $H_P(10)_{under}$ is from the dosimeter worn under the apron.

Landauer enabled its clients to select either monitoring method for those identified by the client as working in fluoroscopic situations. Radiation safety officers have demonstrated a preference to monitor fluoroscopic staff using the one dosimeter method. A recent review of Landauer monitoring results for 2012 found that 70% of fluoroscopic staff were monitored with the one dosimeter method (Yoder and Salasky 2016). It should be noted that when no dose is measured under the apron, the effective dose equivalent for the two dosimeter monitoring protocol reduces to 0.04 $H_P(10)_{over}$ or about 13% of the dose estimated for the one dosimeter method when each dosimeter yields the same $H_P(10)$ dose value. A recent analysis of 2012 monitoring results from the two dosimeter method found only 11% had under apron doses that exceeded the minimum measurable dose (Yoder and Salasky 2016). The multiple accepted ways to estimate the effective dose equivalent introduces complications for the dose reconstruction process because the dosimetry database does not distinguish which method of computing effective dose equivalent was selected for a person. Prior to 2000, the predominant method for monitoring staff wearing leaded aprons was with one dosimeter located over the apron at the collar with no adjustment of the measured $H_P(10)$ value. After 2000, the database contains a mix of effective dose equivalent analysis results. The difficulty from the two dosimeter approach is that neither value of $H_P(10)$ can be predicted from only the effective dose equivalent value because numerous combinations of $H_P(10)_{over}$ and $H_P(10)_{under}$ can result in the same dose value.

In summary, the annual dose values represent different dosimetry quantities depending on the year and regulations in force at that time. Lifetime dose values were not recomputed as the quantities changed; therefore, the lifetime whole body dose estimates in the database equal the sum of the annual doses without respect to the measured quantity. This further limits the utility of the lifetime dose values in the database other than giving a relative ranking to how much dose an individual might have received during their employment history.

Radiation exposure scenarios for medical radiation workers

Many medical procedures involve the use of radiation but these can be distilled into six general exposure scenarios: general diagnostic radiology, fluoroscopically guided procedures, nuclear medicine up through 1999, nuclear medicine from 2000 to the present, radiation oncology up through 1969, and radiation oncology from 1970 to the present (Table 1). These can be described as either low energy photon exposure situations (predominant energies less than 0.1 MeV) or high energy photon energy situations (predominant energies above 0.1 MeV). The demarcation on energy corresponds to the likelihood of the use of leaded aprons and the transition zone at which the conversion factors that relate $H_P(10)$ to mean organ absorbed dose become less energy dependent as discussed later. The time separation for nuclear medicine arises from the introduction of positron emission tomography that mostly relies on fluorine-18 and the decay of the emitted positron into 0.511 MeV photons. Prior to 2000, nuclear medicine procedures were mostly conducted with technicium-99m and to a lesser extent iodine-131 and thallium-204.

The time division for radiation oncology is based on changes in the sources used in brachytherapy and the shift from cobalt-60 to high energy linear accelerators and cyclotrons for teletherapy. The time distinction has minimal impact on dose reconstruction as all radiation oncology that presents an opportunity for significant worker dose would involve high energy photons for which dose conversion factors exhibit little change with increasing energy.

With the exception of fluoroscopically guided procedures, all scenarios assume that 100% of the measured doses were predominantly received with the worker facing the source so that the radiations traversed the body in an anterior to posterior (AP) direction. For fluoroscopic exposures, 75% of the dose is assumed to be received in the AP direction with the remainder from the sides (left lateral, LLAT and right lateral, RLAT geometries). The left side is expected to be preferentially exposed for physicians performing many fluoroscopically guided interventional procedures based on their normal position adjacent to the right side of the patient near the thigh with the physician's body oriented toward the video image displays; although this is not universal. The fluoroscopic and nuclear medicine scenarios are expected to be the most common for the workers having the highest doses. The general radiology scenario presents little risk of high dose because operators of the X ray unit usually stand in shielded control areas or at some distance from the X ray unit during image acquisition. Many radiation workers fall into this category and it is expected that a majority of the randomly selected workers for the MWS cohort with lifetime doses less than 50 mSv will fall into this exposure scenario. A similar situation exists for radiation oncology as radiation therapy staff are not present in the treatment room during irradiation of the patient. An exception is possible prior to the adoption of high dose rate brachytherapy when staff would be present during the insertion and retraction of the radioactive seeds.

Medical staff exposed during nuclear medicine and radiation therapy procedures are assumed not to have worn leaded aprons. The energy of radiations is such that leaded aprons provide little dose reduction. General radiology workers are also assumed not to have worn leaded aprons.

Assigning workers to radiation exposure scenarios

The impracticality of contacting over a thousand institutions to gain information about exposures to workers acquired over many years dictates the need to use account and series code information in the Landauer database to infer the exposure scenario for each member of the cohort for each year of their work. Selected examination of archived dosimetry reports will provide a means to verify the computer assignment routines; in particular, the energies of radiation detected by the dosimeters and whether one or two dosimeters were issued to those using leaded aprons. In addition, database information will be compared with the stored records maintained by a few large hospitals as an alternate, more precise approach to verify the correctness of the assignments and dates of service.

A customer category code assigned by Landauer enables hospitals, small clinics, private practices, and other medical facilities to be separately identified from non-medical facilities. Hospitals and larger clinics are most likely to have most if not all of the exposure scenarios. Fluoroscopically guided interventions are assumed to be constrained to hospitals only. Small

clinics will typically be limited to general radiology, nuclear medicine and/or radiation oncology. The institution's name frequently provides clues as to the type of medical procedures practiced. The series code to which workers are frequently associated in an account can provide information about the type of radiation procedures performed by the department or location when multiple environments may exist. When a code does not indicate a medical specialty, dosimetry reports along with the energy detected by dosimeters in the series can be used to identify the scenario most likely to be found.

The process to normalize annual dose values to $H_P(10)$

The ICRP has published the results of recent calculations (particularly Monte Carlo simulations) to generate absorbed dose distributions in anthropomorphic phantoms for mono-energetic photons incident on the body in various geometries and compiled the results to create tables of conversion coefficients for use in estimating the mean organ absorbed dose (D_T) in various organs per unit of radiation fluence and kerma in air (ICRP 2010). The ICRP has published similar conversion factors that relate fluence and kerma in air to $H_P(10)$ (ICRP 1996). With D_T and $H_P(10)$ each being related to common fundamental dosimetry quantities, it becomes a straightforward process to compute conversion factors that directly relate $H_P(10)$ to D_T for the various irradiation geometries.

The Committee advising the MWS epidemiologists has specified the following adjustments to the annual dose values in the Landauer database so that all values are expressed as $H_P(10)$. Values of mR should be multiplied by 0.9 for radiation scenarios involving lower energy photons (mean energy of 0.05 MeV) and 0.95 for higher energy photons (energies above 0.1 Mev). Values of the restricted dose equivalent index should be multiplied by 1.1 for the scenarios involving lower energy photons and 1.03 for higher energy photon scenarios based on comparisons of the data published in ANSI N13.11-1983 (1983) for the restricted dose equivalent index and in a revised version of the ANSI standard (ANSI 2001) for the slab phantom. With the exception of annual doses for fluoroscopy workers that are stored as the effective dose equivalent, all other annual dose values should be considered as the quantity, $H_P(10)$; although adjustments for the use of a leaded apron must be employed.

The use of leaded aprons introduces the greatest challenges for dose reconstruction. After adjusting for the measured quantity, the dose reconstruction process aims to establish an annual value for $H_P(10)$ that would have been measured on the body (e.g. the chest) as if no apron had been present. Before 2000 when the effective dose equivalent formulas were sparsely used, the annual dose values represent a dose measured above the apron. The measured value of $H_P(10)$ is appropriate for the head region but must be adjusted for the torso organs.

The adjustment for the effects of the leaded apron can be inferred from an assessment of ratios of dosimeters worn over the apron to those worn under the apron. This ratio largely depends on the attenuation characteristics of the apron but also any spatial or geometrical differences in the dose rates at the locations of the dosimeters, differences in dosimeter performance when the dosimeters are not directed at the same angle toward the source and from the change in dose per unit fluence due to shifts in the energy spectra that occur from

photon absorption and scattering in the apron. Apron thicknesses may vary from 0.25 mm of lead equivalent to 0.5 mm and the placement of a dosimeter over the apron is not likely to be in the same place as that worn under the apron. Over apron dosimeters tend to be worn high on the body at the collar level and under apron dosimeters worn on the chest or even waist. Yoder and Salasky (2016) observed over to under dosimeter dose ratios that ranged from 4 to 200 for fluoroscopically-based procedures. The range was influenced by the very low doses measured under the apron but when only under apron dose values above 0.1 mSv were considered, the median ratio was 7.6. These ratios shift when annual summations of over and under apron measurements are examined because many under apron dosimeter values observed during the year failed to exceed the 0.02 mSv detection limit for the dosimeter. The median ratio for annual doses was 17 when the annual under apron dose exceeded 0.1 mSv. Combining this information with calculated attenuation factors for 0.5 mm of lead for 50 keV photons, the Committee has tentatively decided to use a 95% dose reduction factor created by the apron so that all over apron dose values will be multiplied by 0.05.

Relating $H_P(10)$ to mean organ absorbed dose for the lung, brain and other select organs

ICRP Publication 116 presents a series of tables of conversion factors that relate air kerma or photon fluence to effective dose and the mean absorbed dose in 13 primary and 12 secondary or remainder organs and tissues in the male and female body for several irradiation geometries (ICRP 2010). Similarly, ICRP Publication 74 presents conversion factors that relate air kerma and photon fluence to $H_P(10)$ (ICRP 1996). Using both sets of conversion factors enables the derivation of conversion factors that directly relate $H_P(10)$ to effective dose and mean organ absorbed dose. Examples of such conversion factors are plotted in Figures 1–8.

Studies of the survivors of the Hiroshima and Nagasaki atomic bombings have indicated a difference between males and females in the risk of developing lung cancer from exposure to radiation. The radiobiological basis for this risk difference is not clear and NASA has expressed interest to the NCRP in determining whether lung cancer incidence differs between men and women occupationally exposed to radiation as part of the risk assessment for astronauts making an expedition to Mars (Boice 2017). In addition, some reports have examined the incidence of brain cancers in physicians performing fluoroscopically guided interventional procedures (Roguin et al. 2013) and in radiological technologists (Kitahara et al. 2017). The size of the medical worker cohort may shed information about the incidence of brain cancer and other effects on the central nervous system. Leukemia has been of historical interest stemming from early regulations that limited exposure of the red bone marrow. The dose–response for cancer incidence in other organs is an ongoing subject behind the linear no threshold hypothesis (LNT) (NCRP 2018). Figures 2 and 3 present the conversion factors for the lung and brain, respectively as these have been stated to be of most interest to the MWS. Figures 4–7 present information for three organs found in the torso and the red bone marrow that is more widely distributed within the body. These figures demonstrate the efficacy of assessing mean organ doses to other organs once values for

$H_P(10)$ have been established. All figures present conversion factors for both sexes. Figure 8 plots the ratio of the female to male conversion factors for the lung in the AP geometry.

Generally, the AP geometry creates the largest mean organ absorbed dose of the torso organs considered in this review; however, the lateral irradiation geometry leads to larger mean absorbed doses to the brain. Organ and body morphology as well as the structure and composition of tissues intervening between the surface of the body and the organ of interest influence the conversion factors as demonstrated by the lung and brain plots. The conversion factors relating $H_P(10)$ to D_T vary significantly for photons with energies below 0.1 MeV; however, the range of effective energies encountered with the use of X rays that lead to higher worker doses ranges between 0.04 and 0.06 MeV with 0.05 MeV being selected as most typical. Above 0.1 MeV, the conversion factors become less influenced by energy allowing less precision in defining the specific photon energies involved with the higher energy exposure scenarios.

The conversion factors presented in the figures pertain to mono-energetic photons and weighting is required to derive conversion factors applicable to the work environment. Based on the radiation scenario information presented in Table 1, starting values of the energy-weighted conversion factors for the six scenarios are presented in Table 2. The conversion factor for the fluoroscopically guided interventions has been weighted by the relative proportions of the dose received from the AP (75%) and LAT (25%) geometries. The energy-weighted conversion factors presented in Table 2 indicate the relative sensitivity of defining the effective energies. For the lung, the conversion factors increase by about 50% from the X ray to the nuclear medicine environments and for the brain, the change is even less.

The conversion factors represent upper bounds on the organ absorbed dose because the models on which the ICRP data were based cause the body to be uniformly irradiated by a parallel and aligned radiation field. This is an idealized condition not encountered in medical work environments. Most work environments will have spatial variations in dose rate causing the body to be unevenly irradiated. Such uneven irradiation may alter the absorbed energy distribution in an organ. Spatial variations combined with dosimeters being worn at the higher dose points on the body suggest that the conversion factors derived from the ICRP data could over-estimate by an unknown amount the true mean absorbed dose to an organ.

Conclusions

The use of the Landauer database of annual and lifetime doses as the primary tool to select the cohort of medical radiation workers and conduct dose reconstructions presents special challenges. The selection of the medical worker cohort is expected to result in over 1000 institutions being represented with each able to enact various monitoring protocols. The file structure of the database requires extra steps to develop a complete dose history because data must be assembled from multiple institutions as a result of medical workers having a tendency to have worked at many facilities. The size of the medical worker population from which to select the study cohort is too large to permit reconstruction of annual doses

from which to determine lifetime doses for all medical workers prior to selecting the cohort. Therefore, an initial selection protocol using uncertain estimates of lifetime dose is to be used.

The changes in the measured dose quantities along with variations in monitoring protocols add complexity to the process of converting the dosimeter dose values to the personal dose equivalent; especially when leaded aprons were used. Descriptive information in the database can aid in placing workers into a radiation exposure scenario but additional information from other databases and dosimetry reports will likely be necessary to separate those workers who used a leaded apron from those that did not. The effect of photon energy is secondary to the effect of the leaded apron for estimating the mean absorbed dose to the lung.

Once a worker has been associated with a radiation exposure scenario, the process of converting annual values of $H_P(10)$ to mean organ absorbed doses will be relatively straightforward. There is extensive knowledge about the predominant radiations and their energies that workers normally encounter in a medical facility. The regulatory influence to wear dosimeters at the point of highest dose imparts an unknown bias toward over-stating organ doses.

The Landauer database enables an efficient means of studying the medical radiation worker population. An element of consistency is achieved because the dosimetry calibration approaches used by Landauer have been constant over many years and the data is in a standard electronic format that avoids manual data entry from archived files. The Landauer database contains annual dose information back to 1977 and earlier information is available from microfilmed images of dosimetry reports that go back to the early 1960s. The cost to manually retrieve and digitize dose records has been a significant cost for large epidemiological studies such as the MWS. The use of the Landauer database is one approach being used to mitigate these costs.

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Biographies

R. Craig Yoder directed the technical activities and programs at Landauer, Inc. from 1983 through his retirement in 2015. In this capacity he influenced the technologies and measurement protocols used by the Company as it delivered dosimetry services around the world. He currently is using his historical knowledge to advise the MPS epidemiologists regarding the methods to translate personal monitoring information into mean absorbed doses to various organs. He is a Council member of the National Council on Radiation Protection.

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John Boice is President of the National Council on Radiation Protection and Measurements and Professor of Medicine at Vanderbilt University. He is an international authority on radiation effects and served on the Main Commission of the International Commission on Radiological Protection and on the United Nations Scientific Committee on the Effects of Atomic Radiation. He directs the Million Person Study of Low-Dose Health Effects.

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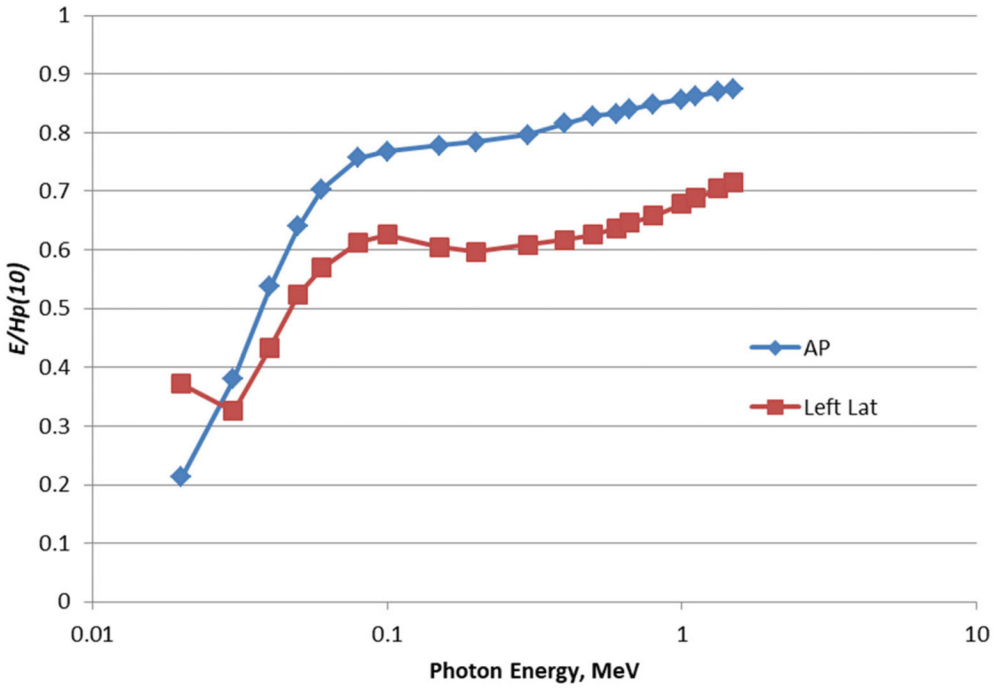

Figure 1.

The ratio of Effective Dose, E, to the Personal Dose Equivalent, $H_p(10)$ for two irradiation geometries in the male anthropomorphic phantom. Data derived from information presented in ICRP Publications 74 and 116 (ICRP 1996, 2010).

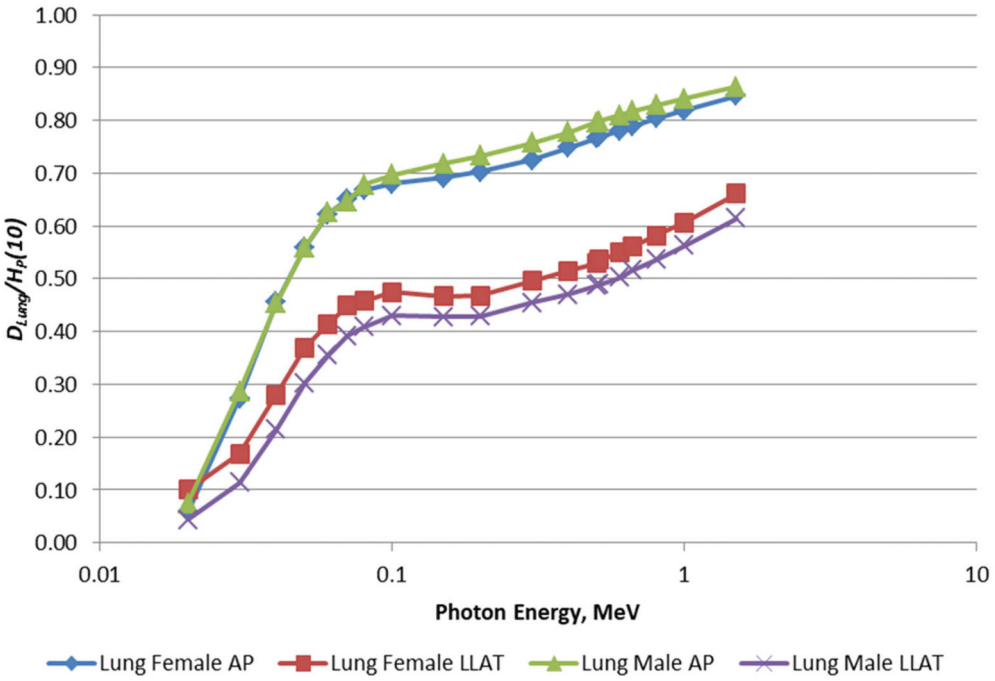

Figure 2.

The mean absorbed dose to the lung for males and females for two irradiation geometries. Data derived from information presented in ICRP Publications 74 and 116 (ICRP 1996, 2010).

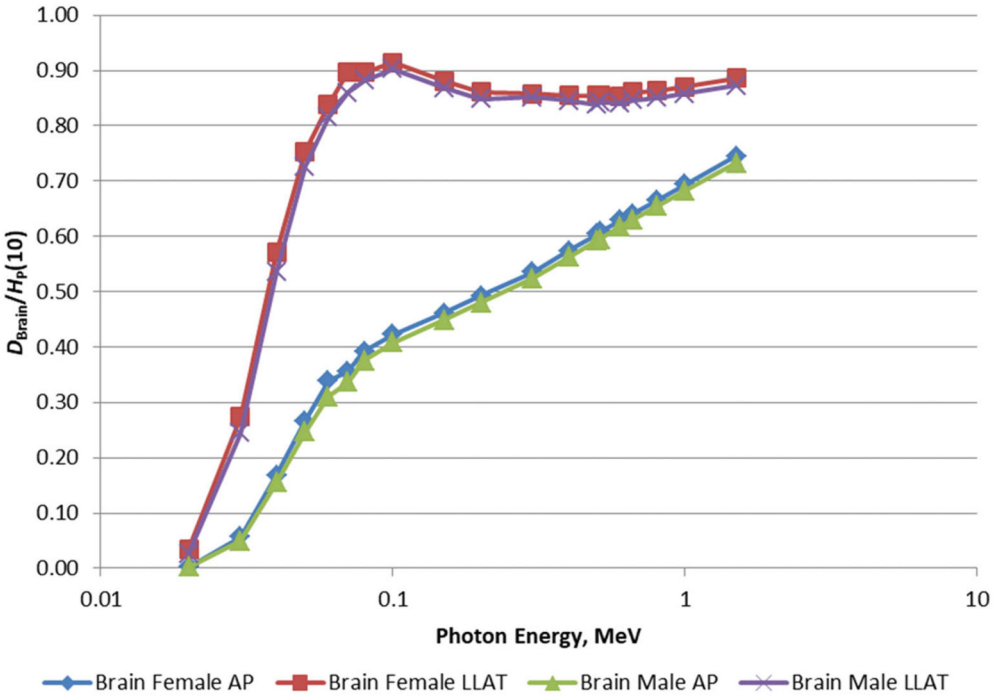

Figure 3.

The mean absorbed dose to the brain per $H_P(10)$ for males and females for two irradiation geometries. Data derived from information presented in ICRP Publications 74 and 116 (ICRP 1996, 2010).

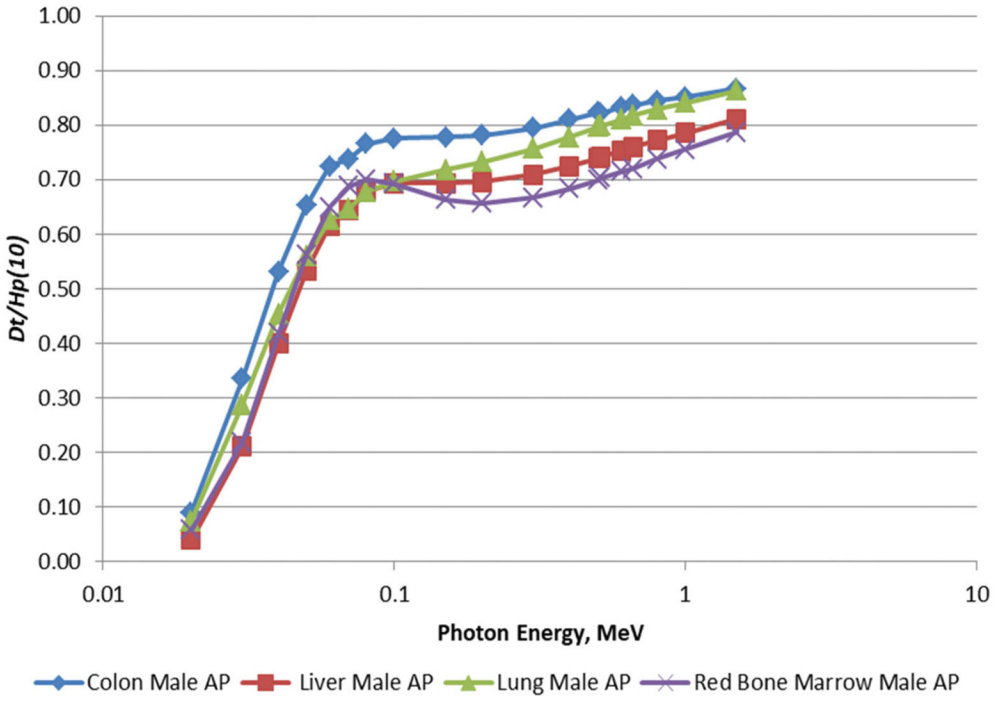

Figure 4.

The mean absorbed dose to four tissues per $H_P(10)$ for the male body in the AP geometry. Data derived from information presented in ICRP Publications 74 and 116 (ICRP 1996, 2010).

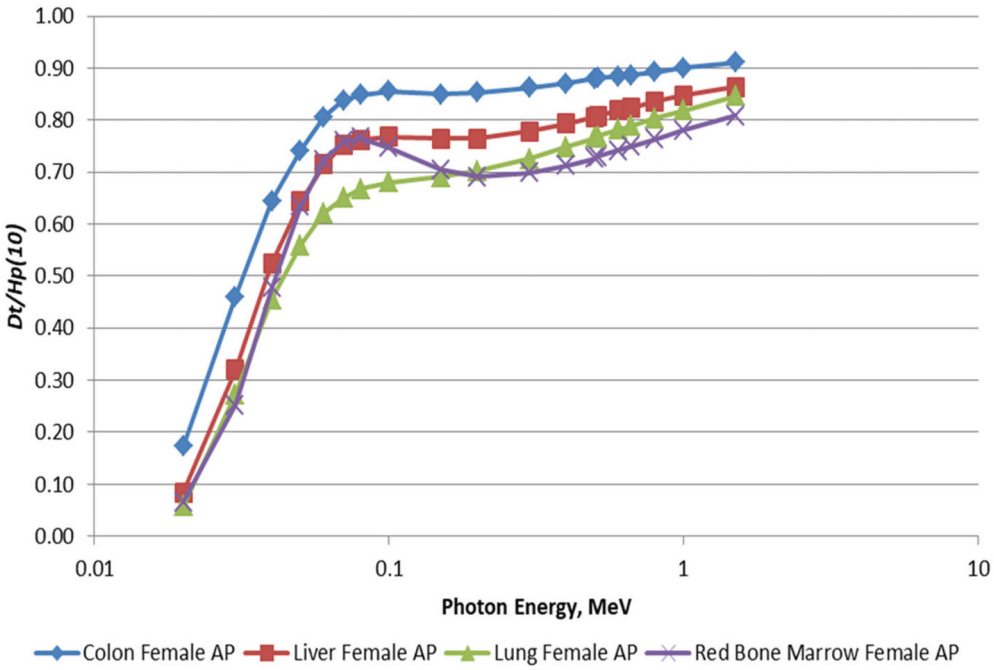

Figure 5.

The mean absorbed dose to four tissues per $H_P(10)$ for the female body in the AP geometry. Data derived from information presented in ICRP Publications 74 and 116 (ICRP 1996, 2010).

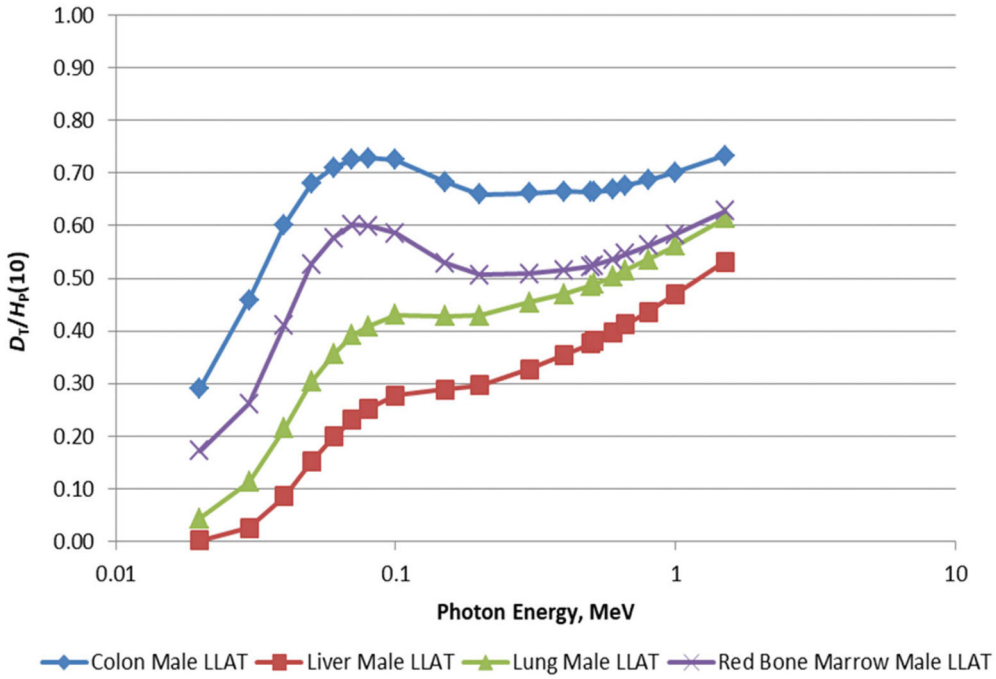

Figure 6.

The mean absorbed dose to four tissues per $H_P(10)$ for the male body in the Left Lateral geometry. Data derived from information presented in ICRP Publications 74 and 116 (ICRP 1996, 2010).

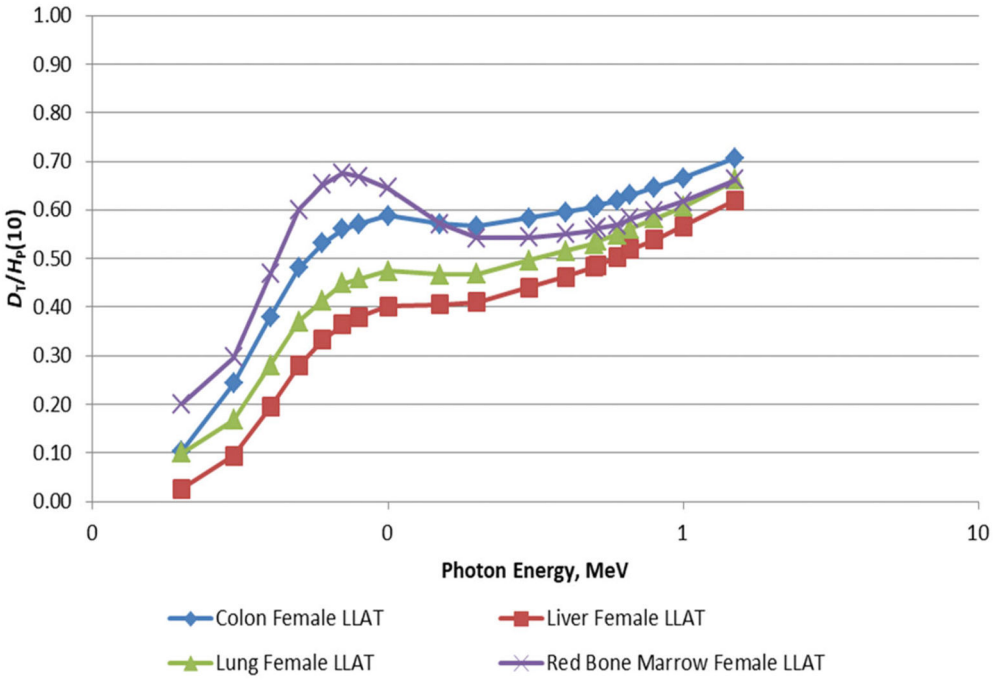

Figure 7.

The mean absorbed dose to four tissues per $H_P(10)$ for the female body in the Left Lateral geometry. Data derived from information presented in ICRP Publications 74 and 116 (ICRP 1996, 2010).

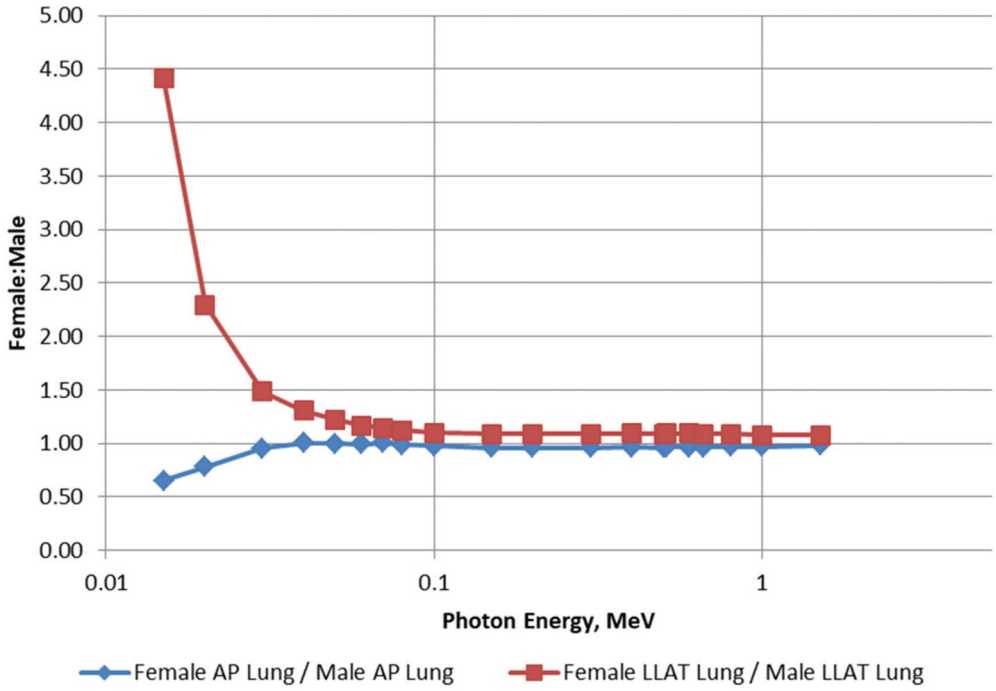

Figure 8.

The ratio of the female to male mean absorbed dose to the lung in the AP and Left Lateral geometries. Data derived from information presented in ICRP Publications 74 and 116 (ICRP 1996, 2010).

Table 1.

Characteristics and assumptions pertaining to radiation exposure scenarios.

Scenario	Radiation sources	Assumed weighted energy	Assumed irradiation geometry	Assumed protection
General radiology	Scattered X rays with mean energies between 0.04 and 0.06 MeV	0.05 MeV	AP	Barriers/leaded aprons
Fluoroscopically guided interventions	Scattered X rays with mean energies between 0.04 and 0.06 MeV	0.05 MeV	75% AP 25% Lateral	Leaded aprons
Nuclear medicine before 2000	Tc-99m, I-131, Tl-201	Mix dominated by 0.14 MeV Tc-99m gamma ray	AP	None
Nuclear medicine after 2000	Tc-99m, F-18, I-131	75% associated with Tc-99m and 25% from F-18	AP	None
Radiation oncology before 1970	Ra-226, Au-198, Cs-137, Co-60	1 MeV	AP	None
Radiation oncology after 1970	Ir-192, Cs-137, I-125	0.35 MeV	AP	None

Table 2.

Conversion factors presently considered to relate $H_P(10)$ to mean absorbed dose to the male and female lung and brain.

Scenario	Male lung	Female lung	Male brain	Female brain
General radiology	0.56	0.56	0.56	0.56
Fluoroscopically guided interventions	0.50	0.51	0.5	0.51
Nuclear medicine before 2000	0.72	0.69	0.45	0.46
Nuclear medicine after 2000	0.78	0.75	0.57	0.58
Radiation oncology before 1970	0.84	0.82	0.68	0.69
Radiation oncology after 1970	0.77	0.74	0.54	0.55