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Memorandum

Using personal monitoring data to derive organ doses for medical radiation workers in the Million Person Study—considerations regarding NCRP Commentary no. 30

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Abstract
The study of low dose and low-dose rate exposure is of central importance in understanding the possible range of health effects from prolonged exposures to radiation. The One Million Person Study of Radiation Workers and Veterans (MPS) of low-dose health effects was designed to evaluate radiation risks among healthy American workers and veterans. The MPS is evaluating low-dose and dose-rate effects, intakes of radioactive elements, cancer and non-cancer outcomes, as well as differences in risks between women and men. Medical radiation workers make up a large group of individuals occupationally exposed to low doses of radiation from external x-ray/gamma exposures. For the MPS, about 100 000 United States medical radiation workers have

[10] C Yoder and LT Dauer were Chair and Co-chair, respectively of NCRP Scientific Committee SC 6-11 that produced Commentary No. 30.

been selected for study. The approach to the complex dosimetry circumstances for such workers over three to four decades of occupation were initially and broadly described in National Council on Radiation Protection and Measurements (NCRP) Report No. 178. NCRP Commentary No. 30 provides more detail and describes an optimum approach for using personal monitoring data to estimate lung and other organ doses applicable to the cohort and provides specific precautions/considerations applicable to the dosimetry of medical radiation worker organ doses for use in epidemiologic studies. The use of protective aprons creates dosimetric complexity. It is recommended that dose values from dosimeters worn over a protective apron be reduced by a factor of 20 for estimating mean organ doses to tissues located in the torso and that 15% of the marrow should be assumed to remain unshielded for exposure scenarios when aprons are worn. Conversion coefficients relating personal dose equivalent, $H_p(10)$ in mSv, to mean absorbed doses to organs and tissues, D_T in mGy, for females and males for six exposure scenarios have been determined and presented for use in the MPS. This Memorandum summarises several key points in NCRP Commentary No. 30.

Keywords: radiation, epidemiology, dosimetry, occupational, monitoring

(Some figures may appear in colour only in the online journal)

1. Introduction

The study of low dose and low-dose rate exposure is of central importance in understanding the possible range of health effects from prolonged exposures to radiation. The One Million Person Study of Radiation Workers and Veterans (MPS) of low-dose health effects was designed to evaluate radiation risks among healthy American workers and veterans [1]. The MPS is a national effort in the United States (U.S.), directed by John D Boice Jr and coordinated by the National Council on Radiation Protection and Measurements (NCRP), with critical support from the Nuclear Regulatory Commission, U.S. Department of Energy, National Aeronautics and Space Agency, U.S. Navy, U.S. Department of Defense, National Cancer Institute, Centers for Disease Control and Prevention, U.S. Environmental Protection Agency, the national laboratories, Vanderbilt University, and Memorial Sloan Kettering Cancer Center. The MPS should provide information on low-dose and low dose-rate effects, and the effects following intakes of radionuclides, evaluating cancer and non-cancer outcomes, as well as differences in risks between women and men. Overall, about 30 individual cohorts comprise the MPS.

Medical radiation workers make up a large group of individuals occupationally exposed to low doses of radiation. Unlike other worker cohorts in the MPS, the medical radiation worker cohort includes a large population of women. Study of the medical radiation worker population, particularly the ability to examine potential risks separately for females and males, will be of particular value for improving and underpinning national and international standards of protection for all workers, the public, and patients. Studies of lung cancer incidence in the survivors of the atomic bombings of Japan indicate females exhibited a threefold higher risk than males [2, 3]. The potential for such a sex-dependent risk factor influences assessments of radiation risks, especially for occupationally exposed groups (e.g. medical radiation workers, nuclear power workers, astronauts, and others). Consequently, the medical radiation worker cohort may provide additional insight into the lung cancer risk for men and women arising from long-term exposure to relatively low levels of radiation.

For the MPS, about 100 000 U.S. medical radiation workers have been identified and are currently being evaluated. The approach to the complex dosimetry circumstances for medical radiation workers over three to four decades of occupational exposure have been initially and broadly described in NCRP Report No. 178 [4, 5], but many of the detailed considerations and approaches for medical radiation workers were not specifically addressed. The NCRP convened a scientific committee of experts (SC 6–11) to address these specific items, with emphasis on estimating lung dose. This Memorandum summarises several key points of the resulting NCRP Commentary No. 30 [6].

Individuals in the medical radiation worker cohort have been monitored with the use of personal dosimeters when potentially exposed to ionizing radiation, and the measurement results have generally been maintained in digital format [5]. Examination of a large database maintained by Landauer Inc. indicates that most medical radiation workers receive very low external radiation doses from x- and gamma radiation. Those individuals who perform certain fluoroscopically guided interventional (FGI) procedures and those who prepare or administer radionuclides for nuclear medicine procedures (especially for positron emission tomography (PET) scanning) are an exception to this generalisation. Medical workers exposed during the early periods examined by the MPS are expected to have received relatively higher doses as a result of the available imaging technologies, higher values of maximum permissible dose limits and design of radioprotective aprons.

Typically for epidemiologic studies [5], it is assumed that the average dose over the entire organ or tissue (organ dose) is the exposure of interest in the analysis. The derivation of organ doses for medical radiation worker cohort members from monitoring data poses difficult problems due to: (a) inhomogeneity of exposure over the body for any given procedure type as organs or tissues may only be partially irradiated (e.g. when medical personnel wear protective aprons), (b) differing degrees and methods of radiation protection across different medical specialties, (c) inconsistent wearing of dosimeters by personnel (i.e. at times choosing not to wear dosimeters in order to avoid investigations) [7, 8], (d) high variability on the workloads of physicians and other clinicians (i.e. the number of procedures of a given type conducted monthly or annually), and (e) changing technology and medical procedure protocols over time.

The purpose of NCRP Commentary No. 30 is twofold: to describe an optimum approach for using personal monitoring data to estimate lung and other organ doses; and to provide specific precautions/considerations applicable to the dosimetry of medical radiation worker organ doses.

2. General guidance from NCRP report no. 178

NCRP Report No. 178 presents an 11-step process to guide the radiation dose reconstruction process to be applied to the worker groups comprising the MPS [5], including: reviewing the potential cohort history, interviewing selected workers, identifying the cohort of radiation workers, reviewing files for individual workers to identify monitoring data, seeking cohort members' monitoring data from other occupational sites, digitising external dose records and internal monitoring data, building exposure scenarios, selecting irradiation geometries and biokinetic models, screening the data to prioritise efforts, estimating annual absorbed doses, and evaluating limitations and uncertainties in those estimates. The dose reconstruction process aims to estimate the mean absorbed dose to one or more specific organs received by a worker during their lifetime from occupational activities. The lifetime organ dose represents the sum of a series of annual organ dose estimates derived from personal and workplace monitoring information computed for each year that the worker was potentially exposed. The organ doses depend greatly on the conditions of exposure including the types of radiation sources, the radiation qualities emitted by the sources, and the spatial relationships between the worker and the sources. The organ doses also depend on other influences such as the effects of scattered radiation, nonuniform irradiation of the body, the effects of protective shielding, and the worker's sex and physical morphology.

For the purposes of the MPS, the medical radiation worker cohort includes physicians and technologists from various medical specialties, nuclear pharmacists, physicists, nurses and allied health care support workers monitored for exposure to medical radiation in similar environments. Also included are veterinarians, chiropractors and dentists. The use of private databases to capture medical radiation worker doses is essential, due to a number of factors. There are a large number of medical establishments using radiation. There is the propensity for medical staff to work for numerous medical establishments, sometimes concurrently and sometimes successively. In addition, there are no national dose registries for medical workers like those that exist for nuclear power plant workers and others. Few databases exist in electronic formats covering the many decades of dose measurements a worker may accumulate. The cohort of medical radiation workers is to be selected primarily from the Landauer database (Landauer, Inc.) that currently offers the most extensive and consistent set of data available from which to understand both the dose levels and radiation risks incurred by large numbers of medical workers in the U.S. This digital dosimetry database contains annual and lifetime results of personal monitoring for workers known to have been monitored since 1977 (with lifetime doses extending back into the mid-1960s) and later years.

A potentially eligible population of >170 000 workers was selected using a stratified sample of 1.7 million medical workers first monitored before 1995 with sufficient identifying information (such as an individual's Social Security Number) to allow vital status tracing. Short-term workers and those with very low cumulative badge doses were excluded because the added costs would not be commensurate with any epidemiologic information gained. Excluded were those monitored for <2 years, those with a cumulative badge dose of <10 mSv, those already studied in other non-medical MPS cohort studies, and those determined to have invalid identifiers. The final study population is expected to consist of about 100 000 medical workers.

Exposure scenarios fall into two general categories: those involving exposure to lower energy x- and gamma rays (e.g. radiology and interventional radiology/cardiology) and those involving exposure to higher energy x- and gamma rays (e.g. nuclear medicine, brachytherapy, radiation oncology). Medical radiation workers are known to work at multiple establishments during their careers and compiling their annual doses relies on the accuracy of personal identifiers that enable a particular worker's dose history to be traced through multiple institutions and employers.

The dose to the organ (e.g. the lung) per unit air kerma or personal dose equivalent depends on the geometry or angle of incidence at which the radiation enters the body. ICRP Publication 116 [9] presents coefficients that relate air kerma, and indirectly, the personal dose equivalent, for anterior to posterior (AP), left and right lateral (LLAT and RLAT), posterior to anterior (PA), rotational (ROT) and isotropic (ISO) exposure geometries. Given the need for the medical staff to attend to patients undergoing a radiological procedure, the dominant irradiation geometry will be AP. Physicians performing FGI procedure may experience a more lateral irradiation geometry due to their physical position relative to the patient from which arise the scattered x-rays that lead to worker doses.

3. Medical worker cohort exposure scenario and organ dose considerations

Using information from ICRP Publications 74 and 116 [9, 10], NCRP Report No. 178 developed a framework for external radiation exposures along with tables and figures of conversion coefficients for relating measured approximations of the personal dose equivalent, $H_p(10)$ (the dose equivalent at a depth of 10 mm in the body expressed in units of mSv) to selected tissue and organ doses, D_T expressed in mGy. The results of personal monitoring obtained from dosimeters worn by medical workers represent the best available data from which to estimate organ and tissue doses for this cohort; therefore, reliance on the Landauer database has become important. The conversion coefficients relating $H_p(10)$ to D_T depend on estimates of the photon radiation energies exposing the worker, the physical orientation between the worker and the radiation source (irradiation geometry), the use of protective shielding and other spatial variations that impart uneven irradiation of the body, and the sex of the worker since morphological differences between males and females can be important for certain organs of interest.

NCRP Report No. 178 previously identified that x- and gamma rays have the greatest influence on organ doses received by medical radiation workers. Although the types of radiation sources and their uses have varied over time, they have generally become highly correlated with several medical specialties, each specialty possessing a combination of unique and common characteristics. NCRP Commentary No. 30 defines six radiation exposure scenarios (and associated radiological characteristics) for medical radiation workers based on a general level of commonality among these factors:

- exposure to x-rays with very little to no use of protective aprons (e.g. general radiology);
- exposure to x-rays with universal or extensive use of protective aprons (e.g. fluoroscopically based radiology and/or cardiology; including FGI procedures);
- exposure during the conduct of nuclear medicine related activities before 2000;
- exposure during the conduct of nuclear medicine related activities since 2000;
- exposure during administration of radiation therapy to patients before 1970; and
- exposure during administration of radiation therapy to patients since 1970.

The year 2000 represents a reasonable demarcation when PET began to materially impact the magnitude of worker doses involved with nuclear medicine-based imaging procedures. The year 1970 represents a similar demarcation in the shift from low dose rate to high dose rate brachytherapy and the resultant use of new radionuclide sources. Exposure to the very high energies employed for teletherapy were not thought to create meaningful staff doses due to isolation of the radiation sources in well-shielded vaults from which staff are barred entry during patient irradiation, thus the focus of the radiation therapy exposure scenarios is on brachytherapy. The six scenarios represent a pragmatic set of bins into which the many different types of medical exposure conditions can be categorised. Table 1 lists several radiation exposure scenario assumptions outlined in NCRP Commentary No. 30.

Regulations and dosimeter testing programs have influenced the quantity measured by personal monitoring dosimeters. Prior to the mid-1980s, dosimeters were designed, calibrated, and analysed to assess the quantity, exposure, expressed in historical units of milliRoentgen (mR). After this period, dosimeters assessed the photon dose at various depths in a 30 cm diameter spherical phantom (individual dose equivalent) until the mid-1990s when a slab phantom (personal dose equivalent, $H_p(10)$) was adopted in response to changes in dosimeter accreditation requirements. By 2000, regulatory guidance allowed the use of formulas to estimate the effective dose from personal dosimeter results. Two specific formulas became more extensively adopted by medical centres for workers involved with FGI procedures. The different measured

Table 1. NCRP Commentary no. 30, radiation exposure scenario assumptions for the medical worker cohort of the MPS[a].

Scenario	Source description	Relative weighting applied to each source
General radiology (x-ray exposure without protective aprons)	70 kV ($\bar{E}$ = 40.5 keV; HVL = 3.30 mm Al) 80 kV ($\bar{E}$ = 44.0 keV; HVL = 3.45 mm Al) 90 kV ($\bar{E}$ = 45.9 keV; HVL = 4.15 mm Al) All spectra evaluated at an angle of 90° from the primary beam.	45% 45% 10%
Fluoroscopy and FGI procedures (x-ray exposure with protective aprons)	70 kV ($\bar{E}$ = 42.2 keV; HVL = 3.52 mm Al) 80 kV ($\bar{E}$ = 45.7 keV; HVL = 3.74 mm Al) 90 kV ($\bar{E}$ = 46.9 keV; HVL = 4.33 mm Al) Weighted spectra underneath 0.4 mm Pb ($\bar{E}$ = 62.8 keV; HVL = 9.3 mm Al) All spectra evaluated at an angle of 45° from the primary beam.	35% 45% 20%
Nuclear medicine before 2000	^{99m}Tc (includes other radionuclides with similar energies, e.g. ^{201}Tl). ^{131}I	95% 5%
Nuclear medicine since 2000	^{99m}Tc (includes other radionuclides with similar energies, e.g. ^{201}Tl). ^{131}I ^{18}F ^{18}F only for exclusively dedicated PET departments	70% 5% 25% 100%
Radiation therapy before 1970	^{226}Ra ^{137}Cs ^{60}Co ^{198}Au	50% 25% 15% 10%
Radiation therapy since 1970	^{192}Ir ^{137}Cs	75% 25%

[a] Reproduced with permission from NCRP Commentary No. 30.

quantities (exposure, individual dose equivalent, personal dose equivalent and effective dose) must be converted into values indicative of $H_p(10)$ at the site of the organ of interest in order to estimate organ dose, a process outlined in NCRP Commentary No. 30 and in NCRP Report No. 178.

The use of protective aprons creates perhaps the greatest amount of dosimetric complexity. The lead-equivalent shielding offered by protective aprons ranges from 0.25 to 0.5 mm attenuating 90%–99% of the x-ray spectra assumed for radiology related scenarios. As such, protective aprons shield the torso and pelvic regions of the body from exposure to radiation. Therefore, the use of a protective apron impedes the direct correlation of monitoring results obtained outside of the apron with the dose received by tissues residing underneath the apron.

Measurements assumed to have been made outside or over the protective apron must be corrected to derive an estimate of $H_p(10)$ that would exist under the apron. The estimated $H_p(10)$ value assessed over the apron can apply directly to the unprotected organs and tissues located in the head. Protective aprons have typically not been used in the nuclear medicine and radiation therapy settings because the photon energies are too high to be effectively attenuated;

therefore, no adjustments for protective aprons should be assumed for nuclear medicine and radiation therapy scenarios.

A significant dosimetric challenge relates to using dose values measured outside the protective apron to predict the $H_p(10)$ dose value that would exist underneath the apron on the torso. The relationship of dose values measured outside the protective apron to estimated $H_p(10)$ is influenced by numerous variables including: the attenuating effect of different lead equivalent thicknesses and designs of protective aprons used by workers, the uncertainty about whether thyroid shields were used and properly worn, the spatial differences in dose rate that exist between the location of dosimeters and the organs of interest, the variation in wearing location of dosimeters, and the shift toward greater average energies of the x-ray spectrum imparted by the protective apron. An additional complication arises from the use of protective aprons when attention becomes focused on the red bone marrow and other tissues widely distributed in the body. The mean absorbed dose to the entire tissue becomes more difficult to estimate. NCRP Commentary No. 30 provides guidance on these important considerations. It is recommended that dose values from dosimeters worn over a protective apron be reduced by a factor of 20 for estimating mean organ doses to tissues located in the torso. For those exposure scenarios that include the wearing of protective lead aprons, most of the red bone marrow will be shielded while some of the marrow will be unshielded due to marrow being present in the head, neck and upper arm skeletal structures. NCRP Commentary No. 30 suggests assuming this unshielded marrow be assumed to be 15%. The dose to the neck area is influenced by the presence (or absence) of thyroid shields and conversion coefficients need to be developed for both cases, especially for gamma exposures.

4. Conversion coefficients for the medical worker cohort of the MPS

NCRP Commentary No. 30 has determined and presented conversion coefficients for each of the six MPS medical worker cohort exposure scenarios and for each sex that relate the measured approximations of the personal dose equivalent, $H_p(10)$ in mSv, to selected tissue and organ doses, D_T expressed in mGy for all the organs for which the ICRP has most recently recommended specific tissue weighting factors (w_T) [11]. As examples, table 2 lists organ-specific (lung, red bone marrow) conversion coefficients relating $H_p(10)$ to D_T for females and males for exposure scenarios for the medical worker cohort of the MPS.

The conversion coefficients for most organs do not materially differ between female and male. The breast is one exception arising from the differences in the mass of the tissue. The reproductive organs have different conversion coefficients due to the anatomical exclusivity of these organs to each sex and their locations in the body. The dependence of the conversion coefficients on photon energy spectra is most evident for the x-ray scenarios where the dominant energies are <0.1 MeV. Several model-based x-ray spectra were developed for NCRP Commentary No. 30 representing spectra generated at peak tube voltages of 70, 80, and 90 kV and possessing average or mean energies ranging from 40.5 to 46 keV. The conversion coefficients for the lung ranged from 0.43 to 0.49 Sv Gy^{-1} for females and from 0.44 to 0.49 Sv Gy^{-1} for males, for the three modeled spectra. As such, the effect of different weighting proportions for these spectra to reflect many different medical diagnostic imaging procedures is not critical compared to the effect from protective aprons. The conversion coefficient for the brain is most sensitive to changes in the x-ray energy due to its being enclosed by the skull composed of higher atomic number elements compared to soft tissues.

Table 2. NCRP Commentary No. 30—organ-specific (lung, red bone marrow) conversion coefficients (Gy Sv^{-1}) relating $H_p(10)$ to D_T for females and males for exposure scenarios for the medical worker cohort of the MPS[a].

Exposure scenario	Detail	Lung		Red bone marrow	
		Female	Male	Female	Male
General radiology	X-ray exposure without protective aprons	0.45	0.46	0.48	0.43
Fluoroscopy and FGI procedures	X-ray exposure with protective aprons[b]	0.57	0.56	0.67 [c] 0.68 [d]	0.60 [c] 0.61 [d]
Nuclear medicine	Before 2000	0.69	0.72	0.71	0.67
Nuclear medicine	From 2000 onwards	0.71 [e] 0.76 [f]	0.74 [e] 0.79 [f]	0.71 [e] 0.73 [f]	0.68 [e] 0.70 [f]
Radiation therapy, primarily brachytherapy	Before 1970	0.79	0.82	0.75	0.73
Radiation therapy, primarily brachytherapy	From 1970 onwards	0.75	0.78	0.72	0.69

[a] NCRP Commentary No. 30 provides conversion coefficients for 13 other organs as well as the lung and red bone marrow (presented here as examples). Table values are presented here from NCRP Commentary No. 30 with permission.
[b] The value of $H_p(10)$ assumed for FGI is that estimated to exist under any radioprotective aprons.
[c] Without thyroid protection.
[d] With thyroid protection.
[e] Multiple radionuclides.
[f] PET only.

5. Dosimetric limitations and uncertainties

A worker's lifetime occupational dose represents the sum of all annual doses received at all known employers. Accompanying each annual dose record in the Landauer database is the lifetime dose accumulated through each year and the year monitoring commenced. Estimates of annual doses received before 1977 that were not stored in the database depend on equally apportioning the lifetime dose present in 1977 among the number of years between the year monitoring commenced and 1977. Although the specific radiation exposure scenario for each year before 1977 may not be discernable for a person, it is reasonable to assume that the scenario selected for 1977 would be appropriate for the earlier years.

Considerable uncertainty may arise associating an annual dose with a radiation exposure scenario. It is impractical to access employment records that would indicate the general work duties from the >1000 medical establishments represented in the cohort. Information about the type of medical establishment (e.g. hospital or private practice) and the departments (e.g. radiology or nuclear medicine) to which workers were assigned exists in the available dosimetry database from which to make intelligent assumptions about the likely radiation exposure scenario causing the majority of a worker's annual dose. When such information is uninformative, but needed, specific dosimetry reports can be examined to identify the most probably exposure scenario. These reports may indicate whether two dosimeters were worn to indicate the possible use of a protective apron as well as the photon energies detected by the dosimeter(s) to distinguish low from high energy photon conditions.

All dosimetric analyses such as those considered in NCRP Reports 158, 163, and 178 [5, 8, 12] possess numerous other sources of uncertainty. The focus in NCRP Commentary No. 30 is on the process for estimating organ doses appropriate for common medical radiation exposure scenarios. NCRP Report No. 178 provides explicit guidance on the treatment of uncertainties and is not repeated in NCRP Commentary No. 30. Unique to the medical radiation worker cohort are the assessments of the types and energies of photon radiations encountered in health care settings. The use of protective aprons, their effective attenuation and the extent aprons compound uneven irradiation of distributed tissues such as the red bone marrow confer the greatest element of uncertainty with respect to the focus of NCRP Commentary No. 30. Uneven irradiation of the body exists as an element of uncertainty for all MPS cohorts; however, the means of addressing uneven irradiation will likely need to be specific to each cohort.

The range of photon energies encountered in the medical setting can also be found in the scenarios developed for the other cohort groups in the MPS. The conversion coefficients relating $H_{\mathrm{p}}(10)$ to D_{T} vary greatest for photon energies <0.1 MeV and for organs located in skeletal structures. The particular nature of the x-ray spectra created for medical imaging has been examined in NCRP Commentary No. 30, and within this setting the use of the average or mean photon energy can be a suitable substitute for a detailed energy spectrum for determining appropriate conversion coefficients. This may not be appropriate for scenarios pertaining to the other cohort groups where certain radionuclides emit discrete energies. Above 0.1 MeV, the conversion coefficients vary less with energy and are less impacted by skeletal features. The delineation between low (<0.1 MeV) and high (>0.1 MeV) energy photon conditions is strongly recommended; however, cases may exist where the predominant energy spectra are unknown or highly mixed, making difficult the selection of an appropriate conversion coefficient. In the absence of any spectral information, the selection of a conversion coefficient should consider the most probable conditions that could yield the specific annual monitoring value based on the general knowledge of the worker population.

The concept of 'missed dose' is another uncertainty factor spanning across multiple cohort groups for whom dosimetry relies on personal monitoring devices. Missed dose is that dose a worker may have received but was less than the minimum detection or recording level of the dosimetry system. Missed doses should not be confused with unmonitored doses that are doses received by a worker when no monitoring device was worn. Missed dose adjustments primarily concern the least exposed members of the cohort because they have the largest number of measurements that yielded results less than the minimum detection or recording limit. Recommended additions to annual doses due to missed doses range from 0.2 to 0.4 mSv yr^{-1} depending on the estimated number of monitoring results that were less than the detection limit or minimum reportable value that comprised the annual dose total.

6. Conclusions

The principal purpose of NCRP Commentary No. 30 [6] is to describe an optimum approach for using personal monitoring data to estimate lung and other organ doses applicable to the medical worker cohort of the MPS and to provide specific precautions/considerations applicable to the dosimetry of medical radiation worker organ doses for use in epidemiologic studies. NCRP Scientific Committee 6–11 applied the NCRP Report No. 178 steps to guide the radiation dose reconstruction process generally appropriate for worker groups comprising the MPS [5] to the medical worker cohort specifically. Conversion coefficients relating $H_p(10)$ to D_T for females and males for six exposure scenarios have been determined and presented for use in the MPS. The limitations and uncertainties associated with such dose reconstruction are acknowledged and discussed in detail in the NCRP Commentary and summarised in this paper.

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Conflicts of interest

Much of the data used to reconstruct doses for the medical radiation worker cohort arises from measurements made by Landauer, Inc. and its predecessors over a period in excess of 50 years. To assure historical accuracy of both technical and administrative data, much of which is unpublished, two members of the Committee, R. Craig Yoder (retired) and Christopher Passmore of Landauer, Inc. were asked to serve by the NCRP. Their participation does not reflect any endorsement of the commercial offerings of Landauer by the NCRP. The respective authors attest that the associations had no influence on their work on this report.

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