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Photon energy readings in OSL dosimeter filters: an application to retrospective dose estimation for nuclear medicine workers

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Abstract

This work investigates the applicability of using data from personal monitoring dosimeters to assess photon energies to which medical workers were exposed. Such determinations would be important for retrospective assessments of organ doses to be used in occupational radiation epidemiology studies, particularly in the absence of work history or other information regarding the energy of the radiation source.

Monthly personal dose equivalents and filter ratios under two different metallic filters contained in the Luxel+® dosimeter were collected from Landauer, Inc. from 19 nuclear medicine (NM) technologists employed by three medical institutions, the institution A only performing traditional NM imaging (primarily using ^{99m}Tc) and institutions B and C also performing positron emission tomography (PET, using ¹⁸F). Calibration data of the Luxel+® dosimeter for various Xray spectra were used to establish ranges of filter ratios from 1.1 to 1.6 for ^{99m}Tc and below 1.1 for ¹⁸F.

Median filter ratios were 1.33 (Interquartile range (IQR), 0.15) for institution A, 1.08 (IQR, 0.16) for institution B, and 1.08 (IQR, 0.14) for institution C. The distributions of these filter ratios were statistically-significantly different between the institution A only performing traditional NM imaging and institutions B and C also performing PET imaging.

In this proof-of-concept study, filter ratios from personal monitoring dosimeters were used to assess differences in photon energies to which NM technologists were exposed. Dosimeters from technologists only performing traditional NM procedures mostly showed Al/Cu filter ratios above 1.2, those likely performing only PET in a particular month had filter ratios below 1.1, and those which showed filter ratios between 1.1 and 1.2 likely came from technologists rotating between traditional NM and PET imaging in the same month. These results suggest that it is possible to distinguish technologists who only worked with higher-energy procedures versus those who only worked with other types of NM procedures.

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⁷Conflicts of interest

The authors claim no conflicts of interest.

Keywords

Occupational exposure; radionuclide; dose assessment; nuclear medicine; dosimeters; personal dose equivalent

1. Introduction

Exposure to ionizing radiation is known to have deleterious health effects, whether deterministic tissue reactions (cataract, skin erythema, sterility) or stochastic (cancer, hereditary defects) (IARC 2000, UNSCEAR 2000). While deterministic and stochastic effects associated with high doses of ionizing radiation exposure are now well-understood, stochastic effects associated with low doses of ionizing radiations are still the subject of many radiobiological and epidemiological studies (UNSCEAR 2000, Brenner *et al* 2003, NRC 2006, Gilbert 2009, Little *et al* 2009). The effects of low-dose radiation exposure on risks of cancer and other serious diseases have been evaluated in population-based (Pierce and Preston 2000, Ron 2003, Huda *et al* 2011, Linet *et al* 2012) and occupationally-exposed (Leuraud *et al* 2015) groups, including nuclear (Schubauer-Berigan *et al* 2015, Thierry-Chef *et al* 2015) and medical workers (Kitahara *et al* 2015, Rajaraman *et al* 2016).

In the United States, radiation exposure to workers is governed by annual permissible limits for occupational exposure, as determined by the U.S. Nuclear Regulatory Commission (NRC 1991). Radiation workers wear dosimeters that measure their personal dose equivalent, $H_p(10)$, representing the dose to soft tissue at 1 cm depth in the body, which is used to demonstrate compliance with radiation protection regulations and assist radiation safety professionals with monitoring and controlling radiation levels to which workers are exposed (ICRU 1993). $H_p(10)$ has been used to calculate mean absorbed radiation doses imparted to specific, radiosensitive organs (Simon *et al* 2006, 2014) for use in occupational studies of radiation-related health effects (Preston *et al* 2016, Kitahara *et al* 2017). To precisely quantify health risks, accurate estimation of organ and tissue doses from recorded or reconstructed $H_p(10)$ is critical.

For studies of medical radiation workers, in particular, it is important to account for the energy and the type of ionizing radiation received when assessing organ dose because these factors are important determinants of the dose to specific tissues (NCRP 2007, NCRP 2010, Simon 2011). Certain medical workers, including those in nuclear medicine (NM), may be exposed to a wide range of photon energies and as is widely understood, photon-tissue interactions (PTI) that lead to an energy deposition in the human body depend highly on the photon energy. Low-energy photons will be more significantly attenuated than high energy photon, leading to large dose variations with increasing depth in the body. Higher energies, which are less attenuated and more penetrative, result in more uniform dose distributions within the body. For example, Simon (2011) shows the absorbed dose to bone marrow per unit air kerma from ^{99m}Tc is about 4 times the dose received from typical photon energies used in diagnostic radiography. Similarly, the mean organ absorbed dose per photon fluence to the male lung when the body is exposed to the 511 keV annihilation photons from ^{18}F is over 7.5 times greater than the dose per fluence resulting from exposure to 50 keV

monoenergetic X-rays, but also twice greater than the dose per fluence resulting from exposure to 150 keV photons representing ^{99m}Tc (ICRP 2010).

When reconstructing organ absorbed doses in occupational radiation epidemiology studies, information on work history, i.e., type of radiological procedures conducted, enables the estimation of the primary photon energy used during radiologic procedures allowing for an adjustment of the dose factor (absorbed dose per unit air kerma) to determine a more realistic estimate of organ dose (Simon 2011). Specific examples of estimating $H_p(10)$ in organ dose calculations include Simon *et al* (2014). However, when work history is not available or highly variable in time, as is often the situation in occupational studies, the uncertainty on reconstructed organ doses can be significant and can even result in bias in the estimated doses.

In this work, we investigated the possibility of using data acquired from the filter readings of personal monitoring dosimeters to distinguish the different photon energies to which workers may be exposed, thereby overcoming the absence of work history in the organ dose reconstruction process.

2. Material and Methods

2.1. Data collection

In our previous study on recorded occupational radiation badge doses in nuclear medicine (Villoing *et al* 2018), annual $H_p(10)$ were collected for 208 technologists formerly or currently employed by one of nine U.S. medical institutions, all using the same dosimetry provider (Landauer, Inc.). For the current study, we requested dosimeter information for a subset of the technologists receiving the highest doses in a single year (2015). The subset was chosen to increase the likelihood that dosimeters received sufficient dose during each monthly record, thereby, limiting the uncertainty associated with the readings from each of the dosimeters filters.

These technologists were distributed among three of the nine institutions to limit the impact of the inter-institutions variability between workloads: one institution (A) only performing traditional NM imaging, using predominately ^{99m}Tc , and two institutions (B and C) performing both traditional nuclear medicine (^{99m}Tc) and Positron Emission Tomography (PET), using ^{18}F .

2.2. Luxel+® dosimeter

Landauer, Inc. supplies dosimetry services based on the Optically Stimulated Luminescence (OSL) Luxel+® dosimeter to the majority of medical establishments in the United States. Like most radiation dosimeters, the Luxel+® dosimeter produces several data values that represent absorbed energy in different energy ranges depending on the particular plastic and metallic filters used. Each filter attenuates different parts of the radiation spectrum so that the relative contribution energy range can be assessed and properly used to calculate $H_p(10)$. The sensors absorb radiation energy in different proportions compared to tissue, and algorithms combining the doses measured under the filters are used to account for these differences.

In the specific case of the Luxel+® dosimeter, four different filters are used for estimating $H_p(10)$:

- An open window (unfiltered area) that allows all photon energies to reach the radiation sensor.
- A plastic filter that eliminates beta particles and extremely low energy photons from reaching the radiation sensor.
- An aluminum (Al) filter that removes some of the lower energy photons preventing them from reaching the sensor.
- A copper (Cu) filter that removes more of the lower and moderate energy photons.

High energy photons, such as those from ^{18}F used in PET (main photon energy: 511 keV), are unaffected by the filters causing the responses of the sensors under each filter to be similar. In contrast, the moderate energy photons from ^{99m}Tc (main photon energy: 140.5 keV) cause the Cu filter sensor to exhibit a smaller response than that of the other filter areas. Therefore, the ratio of the responses measured under each of the filter areas differ ^{18}F compared to ^{99m}Tc . The ratio of the responses under two of the filters, the Al/Cu filter ratio, leads to an estimation of the effective photon energy to which the dosimeter was exposed during its use. With a dose resolution of 0.01 mGy under the filters and an uncertainty of 0.02 mGy on these dose measurements, the corresponding filter ratios are not considered with reasonable certainty below 0.05 mSv.

Al/Cu filter ratios of the Luxel+® dosimeter are represented in Figure 1 for different average photon energy of various X-Ray beams defined by the National Institute of Standards and Technology (NIST) and the International Standards Organization (ISO) to Landauer, Inc. The average X-ray energy was calculated by multiplying the energy of each energy bin by the relative contribution of the fluence in the bin to the total fluence comprising the spectrum. The values were specified by NIST (ANSI 2009) and ISO (ISO 1996) and were not separately calculated in this study.

2.3. Al/Cu filter ratios calculations

The individual Al and Cu filter doses for each technologist were computed in this study by first subtracting the dose under each filter from a control dosimeter stored outside of any radiation areas during the periods of use. Subtracting the background filter dose removed the influence of the background radiation. Control dosimeters accompanied the subjects dosimeters during shipping.

The Al/Cu filter ratio for a dosimeter result was calculated for each monthly dose, by dividing the net Al filter dose by the net Cu filter dose. Our study provides values of monthly $H_p(10)$ and Al/Cu filter ratios for each NM technologist and institution.

Summary statistics (e.g. mean, median, minimum, maximum and Interquartile range (IQR)) were computed for both monthly $H_p(10)$ and Al/Cu filter ratios, for each NM technologist and institution. Comparison of the median Al/Cu filter ratios between institutions A, B and

C were performed using the Wilcoxon rank sum test (Stata v.14.1, StatCorp LLC, College Station, TX). P-values less than 0.05 were considered statistically significant.

3. Results

Monthly badge dose readings and corresponding Al/Cu filter ratios were collected from Landauer, Inc. for 19 NM technologists from the three participating institutions: three technologists from the first institution (A), only performing traditional NM imaging; and 10 and six technologists, respectively, from the two institutions (B and C) performing both traditional NM and PET imaging. Within these three institutions combined, the annual $H_p(10)$ ranged from 1.76 mSv to 13.6 mSv for the 19 technologists, with a median value of 3.60 mSv (IQR, 2.40 mSv; mean, 4.56 mSv).

All 12 monthly badge dose readings were collected for each technologist of institutions A and C. Four monthly readings were missing for technologists of institution B, indicating either missing or unreturned dosimeters.

3.1. Monthly badge dose distribution

A total of 224 monthly $H_p(10)$ values were collected for 2015 and 219 Al/Cu filter ratios were examined; 5 monthly badge dose readings were < 0.05 mSv; thus, the corresponding filter ratios could not be read with reasonable certainty. For the 219 monthly badge dose readings > 0.05 mSv, the monthly $H_p(10)$ varied from 0.07 mSv to 1.60 mSv, with a median value of 0.30 mSv (IQR, 0.31 mSv; mean, 0.39 mSv).

Technologists from institution A received monthly $H_p(10)$ from 0.10 to 0.48 mSv, with a median value of 0.24 mSv (IQR, 0.07 mSv; mean, 0.24 mSv); institution B received monthly $H_p(10)$ from 0.07 to 1.00 mSv, with a median value of 0.26 mSv (IQR, 0.18 mSv; mean, 0.29 mSv); and technologists from institution C received monthly $H_p(10)$, from 0.19 mSv to 1.60 mSv, with a median value of 0.59 mSv (IQR, 0.32 mSv; mean, 0.63 mSv). The distribution of these monthly $H_p(10)$ by technologist and institution is shown in Figure 2.

3.2. Al/Cu filter ratios

The Al/Cu filter ratios varied among the 19 NM technologists from 0.77 to 1.64, with a median value of 1.10 (IQR, 0.20; mean, 1.15). Al/Cu filter ratios from institution A varied from 1.04 to 1.53, with a median value of 1.33 (IQR, 0.15; mean, 1.31). Al/Cu filter ratios from institution B were slightly lower, varying from 0.77 to 1.59, with a median value of 1.08 (IQR, 0.16; mean, 1.11); such as those from institution C, varying from 0.84 to 1.64, with a median value of 1.08 (IQR, 0.14; mean, 1.13).

As shown in Figure 3, the distributions of Al/Cu filter ratios were significantly different between institutions A and B ($p < 0.001$), and between institutions A and C ($p < 0.001$). No significant difference was found between the distributions of Al/Cu filter ratios of institutions B and C ($p = 0.95$).

Monthly $H_p(10)$ by institution are presented as a function of Al/Cu filter ratios in Figure 4.

4. Discussion

In this study, monthly $H_p(10)$ obtained from NM technologists working at three different institutions varied from 0.07 mSv to 1.60 mSv, with a median value of 0.30 mSv. The distribution of $H_p(10)$ varied from one month to another in institutions B and C, with wide variation in doses among technologists (Figures 2B and 2C), which was consistent with our knowledge of NM technologists rotating between traditional NM procedures and PET imaging in these two institutions. Figure 2D illustrates the differences in monthly doses received by technologists within each institution, technologists from institution A having received smaller doses than technologists from institution C, very likely performing procedures such as PET that are suspected to result in higher exposure to the technologist (Chiesa C *et al* 1997). The higher doses observed for Institution C compared to Institution B (which also conducted PET procedures) and A (conducting only general NM) may be attributable to factors other than the performance of PET, such as alternate emphases on radiation safety practices as well as differences in workloads.

In the absence of calibration data for the primary photon energy for ^{99m}Tc (140 keV) or ^{18}F (511 keV), the Al/Cu filter ratios of the Luxel+® system for various X-ray beams (Figure 1) were used to estimate the Al/Cu ratio for these exposures. Concerning ^{99m}Tc , its main photon energy of 140 keV was intermediate to average energies of 139 and 144 keV, which both exhibited yielded Al/Cu filter ratios of 1.20. Hence, the Al/Cu filter ratio for the ^{99m}Tc main photon energy of 140 keV would be expected to be 1.20 ± 0.10 . However, the actual radiation spectrum from ^{99m}Tc also contains some lower energy photons created by Compton scatter interactions with shielding materials and the patient. The analysis of scattered photons in ^{99m}Tc imaging show that most of the scattered photons are comprised in a 20% symmetrical energy window centered on the ^{99m}Tc photoelectric peak of 140 keV (Kojima *et al* 1991); other ^{99m}Tc scattered photons gather around a backscatter energy peak (90.7 keV). Considering the calibration data of the Luxel+® system, the Al/Cu filter ratio for this ^{99m}Tc backscatter energy peak would be expected to be 1.60 ± 0.10 . This information helped establish that the Al/Cu filter ratios for technologists performing traditional NM procedures were expected to range from approximately 1.10 to 1.70, depending on the amount of scattered radiation. Considering that Al/Cu filter ratios function of energy show a constant behavior above 200 keV (Figure 1), the Al/Cu filter ratio for ^{18}F , with a main photon energy of 511 keV, would expectedly be very close to the filter ratios of 1.07 corresponding to average energies at 662 and 1250 keV. According to these Luxel+® responses, Al/Cu filter ratios for ^{18}F were established to range from approximately 0.97 to 1.17 (1.07 ± 0.10).

Distributions of Al/Cu filter ratios were statistically-significantly different between institution A, only performing traditional NM imaging, and institutions B and C, performing both traditional NM (^{99m}Tc), and PET imaging (^{18}F) (Figure 3).

Among NM technologists from institution A, dosimeter data (filter ratios and monthly $H_p(10)$) only could be collected from three technologists for this study, the monthly doses received by other technologists being insufficient to derive Al/Cu filter ratios with acceptable uncertainties. The Al/Cu filter ratios of these three NM technologists varied from

1.04 to 1.53, with a median value of 1.33. Over the 36 Al/Cu filter ratios, 32 were ≥ 1.20 , three were between 1.10 and 1.20, and one was < 1.10 . Analysis suggested that this last value (1.04) was due to an errant Al filter dose measurement. All Al/Cu filter ratios were limited to the range of 1.10 to 1.60, previously identified as corresponding to an exposure to ^{99m}Tc , thus confirming that the three technologists from institution A were only performing traditional NM imaging.

The 111 different Al/Cu filter ratios obtained from 10 NM technologists from institution B varied from 0.77 to 1.59, with a median value of 1.08. Twenty-three of the data were ≥ 1.20 , 28 were between 1.10 and 1.20, and 60 were < 1.10 . These results indicated that the technologists conducted a combination of traditional NM and PET imaging, resulting in the dosimeters being exposed to both the lower photon energies of ^{99m}Tc , with Al/Cu filter ratios between 1.10 and 1.70, and the much higher energies associated with ^{18}F . In such a case, the reliance of Al/Cu filter ratios on the relative amounts of dose from each source (^{99m}Tc or ^{18}F) may result in a spread in the observed ratios. Furthermore, as rotations between PET and traditional NM may not have coincided with the monthly exchange period, some months may reflect a combination of energies and a spread in the ratios. A small demarcation between two clusters of ratios could, however, be observed around an Al/Cu filter ratio of approximately 1.16 for institution B (Figure 4). This demarcation was more visible for institution C, whose 72 Al/Cu filter ratios over 6 NM technologists varied from 0.84 to 1.64, with a median value of 1.08 (similar to institution B), and with 14 Al/Cu filter ratios ≥ 1.20 , 17 between 1.10 and 1.20, and 41 Al/Cu filter ratios < 1.10 . These results similarly indicated that the technologists shared duties in both traditional NM and PET imaging.

These results confirm that Al/Cu filter ratios from monthly dosimeters are related to the energy range of the radiation to which nuclear medicine workers are exposed. Our method may be applied to situations, including organ dose reconstruction for an epidemiologic study, when either the energy of the radiation source is unknown or when work history is limited or unavailable. However, we conservatively estimated uncertainties of 0.1 around the Al/Cu filter ratios for ^{99m}Tc and ^{18}F to account for the combined uncertainty arising from measurement precision, variations between the photon energy spectra used for calibration and that found in the clinical environment, and the influence on dosimeter response of wearing positions on the body, resulting in a small overlap in the range of possible filter ratios for these two radionuclides. This method could be used for discriminating technologists performing NM procedures from those specialized in conventional radiology or fluoroscopically-guided interventional (FGI) procedures, with Al/Cu filter ratios for the latter two disciplines expected to vary from 2 to 6, assuming average photon energies between 40 and 70 keV. Such a method could also be expanded to assessments of doses for other types of radiation workers.

The Al/Cu filter ratios reviewed in this study originated from dose measurements made for the year 2015 using the Luxel+® dosimeter used by Landauer, Inc. since 2001 with an exception of its previous and nearly identical dosimeter Luxel® (introduced in 1998). Prior to 1998, Landauer, Inc. relied on the Gardray® photographic film dosimeter, whose data resides on microfiche and hardcopy that require extensive cross referencing with dosimetry

reports to assemble a dataset, in comparison with the Luxel+® information that can be more easily retrieved from storage in electronic formats. Despite the great effort required for retrieving older dosimeter results, the Gardray® dosimeter could reveal even greater differences in filter dose ratios compared with the Luxel family of dosimeters, the photon response of photographic film exhibits being much more influenced by the photon energy. For example, according to Landauers calibration data, the relative filter ratio between photons from ^{137}Cs and 50 keV X-rays, approximately of a factor 3 for the Luxel+® dosimeter, would represent a factor 14 for the Gardray® dosimeter. Film dosimeter data may, therefore, be more revealing about the energy differences between the medical disciplines than OSL and more precise as to the energies to which a subject was exposed.

5. Conclusion

In this proof-of-concept study, ratios of readings from the Al and Cu filters used in personal monitoring dosimeters were used to approximate photon energies exposing NM technologists. Dosimeters from technologists only performing traditional NM procedures mostly showed Al/Cu filter ratios above 1.2, those likely performing only PET in a particular month had filter ratios below 1.1, and those which showed filter ratios between 1.1 and 1.2 likely came from technologists rotating between traditional NM and PET imaging in the same month. These results suggest that it is possible to distinguish technologists who worked with higher-energy procedures, such as PET, versus other types of NM procedures. In theory, this methodology could be used to distinguish photon energies from radionuclide exposures in nuclear medicine from photon energies corresponding to other types of medical radiation procedures (x-rays, computed tomography, fluoroscopically-guided interventional procedures, etc.). For epidemiologic studies in which the radiation source is not known and work history is unavailable, such information could be of value for assisting in deriving more accurate organ doses and for reducing both bias and uncertainty in organ dose estimates.

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Figure 1.
Aluminum to copper (Al/Cu) filter dose ratios by X-Ray beams (Landauer, Inc).

Figure 2.

Box-and-whisker plot of the distributions of monthly $H_p(10)$ by technologists from institution A (A), from institution B (B), from institution C (C), and grouped per institution (D) in 2015 (with minimum, median, maximum, first quartile Q1 and third quartile Q3).

Figure 3. Box-and-whisker plot of the distributions of Al/Cu filter ratios from institution A, B and C in 2015 (with minimum, median, maximum, first quartile Q1 and third quartile Q3).

Figure 4.
Distribution of 2015 monthly $H_p(10)$ in function of the corresponding Al/Cu filter ratios from institution A, institution B and institution C.