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DEVELOPMENT AND TESTING OF A THERMOLUMINESCENT DOSEMETER FOR MIXED NEUTRON-PHOTON-BETA RADIATION FIELDS

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ABSTRACT

A new four-element thermoluminescent (TL) dosemeter and dose evaluation algorithm have been developed and tested to better characterize personnel exposure in mixed neutron-photon-beta radiation fields. The prototype dosemeter is based on a commercially available TL card (with three LiF-7 chips and one LiF-6 chip) and modified filtration elements. The new algorithm takes advantage of the high temperature peak characteristics of the LiF-6 element to better quantify the neutron dose component. The dosemeter was tested in various radiation fields, consisting of mixtures of two radiation types typically used for dosemeter performance testing, as well as mixtures of three radiation types to simulate possible exposure conditions. The new dosemeter gave superior performance, based on the tolerance levels, when using the new algorithm as compared to a conventional algorithm that did not use the high temperature peak methodology. The limitations and further improvements are discussed.

OBJECTIVE

The objective of this work was to characterize the response of the prototype dosemeter and develop an algorithm utilizing the high temperature peaks of TLD-600 to quantify the neutron component of the field [(1)]. The dosemeter performance was tested in various mixed fields and the algorithm was compared to an algorithm that did not utilize the high temperature peaks.

DOSEMETER DESIGN

The Harshaw 7776-1161 card was used. The standard Harshaw 8814 dosemeter holder was modified to give a configuration as shown in Table 1. This dosemeter design is comparable to the dosemeter design of thick element 4 previously described [(1)], except that the thin element in position 3 is 0.15 mm versus 0.09 mm thick. The thinner chip is not currently routinely supplied in the standard dosemeter due to manufacturing and performance issues. Individual element correction coefficients were determined and applied to normalize the response of the chips to the mean of the population.

IRRADIATION AND PROCESSING

A total of 192 dosemeters were exposed at Pacific Northwest Laboratory to a series of American National Standards Institute (ANSI) sources [(2)]. A total of 11 single source, 29 dual source and 6 triple source exposures were performed at dose ratios up to 3:1. The dosemeters were read on a Harshaw 8800 automated hot gas reader using a linear time-temperature profile from 50° C to 300° C, heating at 25° C/second. The glow curve data in nC was used, taking channels 96 through 145 as the main dosimetric peaks 3, 4, and 5, and channels 146 through 200 as the high temperature peaks 6 and 7 of the TLD-600 element. This followed established methodology [(3)]. Channels 89 through 138 were taken as the main dosimetric peaks for the thin element in position 3, since the thinner chip heated at a faster rate than the thicker chips.

ALGORITHM DEVELOPMENT

The single source exposures were used to determine response functions for the four TL elements to different radiations. The latest ANSI exposure to dose conversion factors [(2)] were used. An unpublished conversion factor was used for ^{241}Am [(4)].

In the following discussion, sensitivities, responses and doses will be designated by S, R and H, respectively. Photons, betas and neutrons will be designated as p, b and n. Deep and shallow doses will be designated as d and s. Th is the response of the high temperature peaks of element 4 (peaks 6 and 7) and Tl is the response of the low temperature peaks of element 4 (peaks 3, 4 and 5). The K value is defined to be the TL signal ratio between peaks 6-7 and peaks 3-7.

In the algorithm utilizing the high temperature peak, the presence of neutrons is determined by calculating the K value from element 4. If the K value is less than 0.03, which theoretically corresponds to a photon to neutron dose ratio of 100 to 1, it is assumed that the field has no neutrons. The photon energy is determined by either the element 4/2 ratio if no neutrons are present, or the element 1/2 ratio if neutrons are present. The Cd-filtered element 4 gives a better photon discrimination than the Cu-filtered element 1. The Cu filtration is too thin to be useful for photons above 120 keV. However, the Cu filter must be used for photon energy determination when any neutrons are present. The following equations are used, as derived in a previous work [(1)]:

$$Hn = \{[(1-Kp)Th - KpTl] / (0.146 - Kp)\} / S4n \qquad (1)$$

$$R4p = (-0.854\ Th + 0.146\ Tl) / (0.146 - Kp) \qquad (2)$$

$$Hpd = R2/S2pd \qquad (3)$$

$$R3b = R3 - Hps\ S3ps \qquad (4)$$

$$Hb = R3b/S3b \qquad (5)$$

In the conventional algorithm that does not utilize the high temperature peak, the photon energy is based on the Cu-filtered element 1. With equations 3-5 above, the following equation is also used:

$$Hn = (R4 - Hpd\ S4pd) / S4n \qquad (6)$$

In these algorithms, the constant values shown in Table 2 are used. Note that S4n for the new algorithm includes the response from peaks 3-7, but only peaks 3-5 for the conventional algorithm. These values are constant with dose over the two orders of magnitude tested, from 0.03 to 15 mSv.

RESULTS AND DISCUSSION

The lower limit of detection (LLD) was calculated for each set of dosemeters following ANSI methodology (2). The LLD for all radiation fields tested for the new algorithm was < 40 mSv shallow and 20 mSv deep, compared to < 40 mSv shallow and 10 mSv deep for the conventional algorithm, after 3 weeks of storage.

To evaluate the performance, the tolerance levels were calculated as defined by ANSI (2). A maximum level of 0.35 is considered to be acceptable performance for a personnel dosimetry system. Table 3 shows that the new algorithm has better overall tolerance levels than the conventional algorithm for the tested irradiation fields.

As shown in Table 4, when considering only the neutron component of the mixed field cases, the performance of the new algorithm is markedly better. The new algorithm passed all mixed field exposures, while the conventional algorithm failed in two of the mixed field exposures. It is also noteworthy that the standard deviations of the tolerance levels are smaller for the new algorithm that indicates a more consistent performance over the mixed radiation fields that were tested.

The dosemeter design and algorithm are limited in two aspects, just as other 4-element dosemeters are, in that the energy of the beta and neutron components of the mixed field need be known to give accurate results.

To test if the algorithm would be usable if the beta energy was unknown, the algorithms were modified by using an average beta sensitivity value and the results are shown in Table 5. As expected, larger (but still acceptable) tolerance levels are found in the shallow dose estimations only. This beta energy limitation of many dosemeter systems is well known (5). Another standard algorithm (6) takes advantage of a logarithmic relationship between the ratio of elements 2 and 3 and shallow dose. This is possible when there is much less filtration over element 2. Our dosemeter design effectively stopped all the betas from reaching element 2.

The other limitation, the energy of the neutron field, is more problematic. There is an order of magnitude difference in the sensitivities of element 4 to moderated versus unmoderated neutrons. It is known that for any albedo dosemeter to give accurate results, the neutron field must be characterized by other methods, e.g. Bonner Sphere spectroscopy or 9” to 3” ratio.

To further test the algorithms in more rigorous mixed field conditions, mathematical calculations were made using average element responses. Four radiation sources (x-ray, beta, neutron, and high energy photon) at various mixture ratios of up to 5:1:1:1 were simulated. Since these are single calculated exposures, the tolerance level could not be calculated. The performance quotient was used as a measure of the accuracy of the algorithms and the results are shown in Table 6. The new algorithm is also superior to the conventional algorithm in these simulations, especially in the cases where there is a significant ^{137}Cs dose. This is due to the fact that the conventional algorithm underestimated the photon energy, thus underestimating the dose. The Cu filter is not thick enough to differentiate photons above 120 keV. In the new algorithm, the Cd filtered element, combined with the Kp methodology, properly identified the photon energy.

The dosemeter and new algorithm were designed for mixed field use. While standard ANSI testing methods only use mixtures of two fields at a maximum 3/1 dose ratio, the algorithm gave superior results in actual 3 field mixtures as well as simulated 4 field mixtures at dose ratios up to 5/1.

A dosemeter with approximately 300 mg/cm^2 over element 2 could be used to account for the beta energy issue. The algorithm would have to be modified somewhat to account for the additional beta response, but the basic concept of the high temperature peak method would not change. A thicker Cu filter could be used to achieve better photon discrimination. It would also be useful to test the dosemeter and algorithm under actual field conditions. Laboratory testing is idealized, and not subject to the variables such as geometry and ratios of mixtures that are encountered in the field.

References

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Table 1. Dosemeter design showing elements and filtration.

Position	Material	Thickness (mm)	Original Filtration ($mg.cm^{-2}$)	Added Filtration ($mg.cm^{-2}$)	Total Filtration ($mg.cm^{-2}$)
1	TLD-700	0.38	242 ABS + 91 Cu	567 Acrylic	900
2	TLD-700	0.38	106 ABS + 894 PTFE	----	1000
3	TLD-700	0.15	17 Mylar	----	17
4	TLD-600	0.38	300 ABS	713 Cd	1013

Table 2. Values used as constants in equations 1 - 6.

	New Algorithm	Conventional Algorithm
S4n (mod Cf-252)	34.82 nC/Sv	29.61 nC/Sv
S4n (bare Cf-252)	4.18 nC/Sv	3.54 nC/Sv
S3b (Tl-204)	0.78 nC/Sv	0.78 nC/Sv
S3b (Sr-90/Y-90)	1.57 nC/Sv	1.57 nC/Sv
Kn	0.146	

Table 3. Tolerance levels for all tested fields.

Tolerance Level	New Algorithm	Conventional Algorithm
Sum		
shallow	4.03	4.26
deep	3.20	3.53
Average		
shallow	0.076	0.080
deep	0.060	0.067
Standard Deviation		
shallow	0.042	0.053
deep	0.044	0.051
Range		
shallow	0.01 - 0.17	0.02 - 0.30
deep	0.00 - 0.17	0.00 - 0.19

Table 4. Tolerance levels for neutron dose estimation.

Tolerance Level	New Algorithm	Conventional Algorithm
Sum	1.73	3.15
Average	0.10	0.17
Standard Deviation	0.06	0.16
Range	0.02 - 0.23	0.04 - 0.56

Table 5. Tolerance levels for all tested fields using an average beta sensitivity.

Tolerance Level		New Algorithm	Conventional Algorithm
Sum			
	shallow	7.01	7.19
	deep	3.20	3.53
Average			
	shallow	0.132	0.136
	deep	0.060	0.067
Standard Deviation			
	shallow	0.081	0.085
	deep	0.044	0.051
Range			
	shallow	0.01 - 0.35	0.02 - 0.35
	deep	0.00 - 0.17	0.00 - 0.19

Table 6. Performance quotients for the new and conventional algorithm from simulated irradiation ratios for shallow, deep, neutron and beta dose.

Mixture M30/^{204}Tl/^{252}Cf(D_2O)/^{252}Cf/^{137}Cs	Algorithm	s	d	n	b
1/1/1/0/1	new	0.00	0.00	-0.11	0.00
	conv	0.00	-0.14	-0.15	0.00
1/1/0/1/1	new	0.00	0.00	-0.04	0.00
	conv	0.00	-0.14	-0.03	0.00
3/1/1/0/1	new	0.00	0.00	-0.11	0.00
	conv	0.00	-0.07	-0.15	0.00
1/3/1/0/1	new	0.00	0.00	-0.11	0.00
	conv	0.00	-0.14	-0.15	0.00
1/1/3/0/1	new	0.00	0.00	-0.11	0.00
	conv	0.00	-0.14	-0.15	0.00
1/1/1/0/3	new	0.00	0.00	-0.11	0.00
	conv	0.00	-0.20	-0.15	0.00
5/1/1/0/1	new	0.00	0.00	-0.11	0.00
	conv	0.00	-0.05	-0.15	0.00
1/5/1/0/1	new	0.00	0.00	-0.11	0.00
	conv	0.00	-0.14	-0.15	0.00
1/1/5/0/1	new	0.00	0.00	-0.11	0.00
	conv	0.00	-0.14	-0.15	0.00
1/1/1/0/5	new	0.00	0.00	-0.11	0.00
	conv	0.00	-0.21	-0.15	0.00
3/1/0/1/1	new	0.00	0.00	-0.04	0.00
	conv	0.00	-0.07	-0.03	0.00
1/3/0/1/1	new	0.00	0.00	-0.04	0.00
	conv	0.00	-0.14	-0.03	0.00
1/1/0/3/1	new	0.00	0.00	-0.04	0.00
	conv	0.00	-0.14	-0.03	0.00
1/1/0/1/3	new	0.00	0.00	-0.04	0.00
	conv	0.00	-0.20	-0.03	0.00
5/1/0/1/1	new	0.00	0.00	-0.04	0.00
	conv	0.00	-0.05	-0.03	0.00
1/5/0/1/1	new	0.00	0.00	-0.04	0.00
	conv	0.00	-0.14	-0.03	0.00
1/1/0/5/1	new	0.00	0.00	-0.04	0.00
	conv	0.00	-0.14	-0.03	0.00
1/1/0/1/5	new	0.00	0.00	-0.04	0.00
	conv	0.00	-0.21	-0.03	0.00