A THERMOLUMINESCENCE DOSIMETRY SYSTEM FOR USE
IN A SURVEY OF HIGH-ENERGY BREMSSTRAHLUNG DOSIMETRY*C.G. Soares and M. Ehrlich
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A thermoluminescence dosimetry system suited for a survey of high-energy bremsstrahlung in U. S. radiation-therapy departments has been selected and calibrated. The experiments leading to the choice of the recommended operational characteristics, including dosimeter handling, annealing and readout, dosimeter stability in the contemplated mode of operation, dosimeter response over the photon-energy range to be covered, irradiation geometry and irradiation level are treated in detail. Results are reported of a pilot study involving the shipment of a typical survey assembly (a plastic phantom loaded with a set of dosimeters) for irradiation in one U. S. therapy department and the overall uncertainty of the proposed survey procedure is discussed.

Introduction

The objective of this study was to design, evaluate and calibrate a mailable dosimeter system suited for a survey of the dosimetry in bremsstrahlung beams used in the United States' radiation-therapy departments. The actual surveying will be conducted by the Bureau of Radiological Health (BRH), who supported this work. Only beams with maximum bremsstrahlung energies between 4 and 10 MeV were to be considered, and the survey system was to be similar to the one used by the BRH for other on-going dosimetry surveys. The system was to be capable of dose interpretation with an uncertainty of less than 5 percent.

Based on early results of tests of a water and a Lucite phantom, and following the suggestions of an AAPM liaison committee, it was decided to do all further work with the Lucite phantom. Although this will result in a more expensive mailing kit, a higher degree of reproducibility is expected than with a mailing kit such as that used by the IAEA.² (The IAEA holder is loaded with dosimeters by the participants, who then insert it into their own water vat.) After further discussions, it was agreed that BRH, in their instructions to the participants, would ask them to administer to the Lucite phantom, at a depth of 10 cm, the dose computed for a depth of 10 cm in water, i.e., carry out the irradiations as if the phantom were water rather than Lucite. As a result, we henceforth determined high-energy bremsstrahlung absorbed doses at this depth. We also decided to carry out the main bulk of the high-energy bremsstrahlung calibrations at the 1.0-Gy level. This removes the need for additional annealing procedures to eliminate interference from spurious signals, possibly associated with deeper, hard-to-empty electron traps.

The Selected TLD System

The TLD system used for most of these studies was the Harshaw 2000D** hot-nitrogen reader. With this instrument, up to 52 dosimeters can be read out auto-

matically in sequence. The readout cycle is fixed at 15 sec and only the temperature and the flow rate of the nitrogen are adjustable.

The dosimeters used were the Harshaw TLD-100 (LiF) chips, .32 cm x .32 cm x .08 cm, identical to those used at BRH.³ The LiF (TLD-100) dosimeters were never exposed to direct sunlight or any other illumination containing a large ultraviolet component. A vacuum pickup was used for dosimeter transfer. Between experiments, the LiF (TLD-100) dosimeters were annealed in blocks of 100 on a stainless-steel tray. Pre-irradiation annealing consisted of first placing the loaded trays for 1 hour in a 2-KW muffle furnace maintained at a temperature of 400°C; then allowing them to cool for 30 minutes on a Transite (asbestos) surface and subsequently placing them for 1 hour in a CENCO laboratory oven maintained at 100°C. After another cooling cycle on the Transite sheet, the dosimeters were ready for the next irradiation. Immediately preceding readout, the dosimeters were loaded into the Harshaw disc-type readout holders and the holders were placed in the 100°C CENCO oven for another 10 minutes of heating, followed again by cooling on Transite.

Calibration Procedure

Characterization of dosimeter response (TL signal) can be done either by batch or an individual basis. Both involve reproducible reference irradiations. For all experiments described, these irradiations were performed in a cobalt-60 gamma-ray beam with the dosimeter under an equilibrium thickness of 5 mm of Lucite. Exposures were administered for a fixed length of time (90 s), and were in the 4-to-6 R range. If dosimeter identity is maintained during this procedure, it is possible to correct the subsequent response of each dosimeter for changes in individual sensitivity. We performed this type of individual calibration between any two successive uses of the dosimeters. The sensitivity assigned to each dosimeter in a particular use cycle was the average of the sensitivities obtained in the preceding and the following calibration cycle.

An alternate approach is to select a batch of dosimeters such that the dosimeter sensitivity falls within a certain range of values. The average of this group of sensitivity values is then used to characterize the batch for comparisons between experiments. We found that when the histories of all dosimeters in a batch were similar, the dispersion of dosimeter sensitivities (as given by the standard deviation from the mean) reproduced well over many use cycles. In general, the batch-calibration approach leads to less precise results, however, since, in practice, it is not feasible to select a dosimeter batch with initial sensitivities differing from each other by less than ± 3 to ± 5 percent and dosimeter histories are not necessarily similar, a condition that may lead to significant changes in sensitivity.

For most of the experiments described, irradiations were made in the afternoon, with readout the following morning, i.e., after approximately 16 to 18 hours. This allowed for extended irradiation periods (up to as much as 2 hours) without any significant difference in fading of dosimeter response between irradiation and readout.

*Reference 1 is an expanded version of this paper.

**Commercial product identification does not imply a recommendation or endorsement by NBS, nor does it imply that NBS considers the identified products to be the best available for the purpose.

Reader Characteristics

All readouts were performed with the hot-nitrogen reader, Harshaw Model 2000D, at a gas temperature of 300°C ($\pm 10^\circ\text{C}$) and a nitrogen flow rate of 4.0 (± 0.3) l/min. This was the maximum flow rate attainable with this reader at this temperature.

Current from the photomultiplier tube (PMT) was fed to a fixed-scale current integrator where it was digitized for display. The analog signal was also monitored with an analog plotter for recording glow curves. The integral in digital form initially was converted to serial Ascii code for printout with a standard teletypewriter. This necessitated paper-tape storage of the data, for which retrieval for analysis is rather slow. To remedy this, an off-the-shelf microcomputer was obtained and programmed to accept and to display the serial data and to store them on 5" floppy disks. This system allows compact storage of a large amount of data (from five to forty thousand readings per disk) with quick and easy retrieval for analysis. Thus only simple programs were required for such tasks as individual calibration corrections and statistical analyses.

Results of Experiments

Dependence of LiF (TLD-100) Sensitivity on Photon Energy in the Range from about 10 keV to about 1 MeV

Because of the relatively heavy filtration in the accelerator beams*, it is not expected that there will be an appreciable contribution of low-energy photons in the primary bremsstrahlung beam. This is borne out by the spectrometry results of L. B. Levy et al⁵ who find a low-energy cutoff at about 0.4 MeV in the spectrum of the beam from an 8-MV Mevatron, having, among other filtration, a tungsten-copper flattening filter of more than 1 cm in thickness in the primary beam. However, as the beam enters the phantom, considerable buildup of a low-energy component is expected. In fact, according to the calculations first carried out by Spencer and Fano⁶, a spectral peak located between 50 and 100 keV (regardless of source energy) gradually grows in importance as the depth of penetration into the phantom is increased. For the resulting photon spectra at a depth of 10 or 15 cm in the phantom (15 cm of water representing over 1 mean-free path for a 1-MeV photon and about one-half of one mean-free path for a 4-MeV photon) the effect on the response of the LiF (TLD-100) of the contribution to absorbed dose from the photons in the vicinity of the low-energy peak may not be negligible, particularly for a 4-MV accelerator. (Note that, for a 1-MeV photon, the contribution to absorbed dose at a depth of 1 mean-free path amounts to about 9 percent.)

Because of the presence in the bremsstrahlung beam of a photon component in the energy region in which dosimeter response was not expected to be independent of photon energy, a study was carried out with batch-calibrated dosimeters annealed during readout in the Harshaw hot-nitrogen reader, having sensitivities lying within a ± 2 percent band. The radiation spectra were those of the heavily filtered NBS low-energy standard bremsstrahlung beams⁷ and of the NBS standardized cesium-137 and cobalt-60 gamma-ray sources. Identical irradiations were administered to four samples each at three different exposure levels between about 120 and 800 mR, for which supralinearity proved to be negligibly small over the range of photon energies employed. For all but the cobalt-60 and cesium-137 gamma irradi-

* The 10-MV bremsstrahlung beam from a Clinac-18 is filtered with about 2 cm of tungsten, while the 4-MV bremsstrahlung beam from a Clinac-4 has a lead-antimony flattening filter of a maximum thickness of 1 cm.⁴

Fig. 1 Dependence of Dosimeter Sensitivity on Photon Energy in the Range from about 0.03 to 1 MeV. Response per unit of exposure is plotted relative to that for cobalt-60 gamma rays.

ations, the samples were irradiated bare, supported on a Bakelite strip. For the cobalt-60 and cesium-137 irradiations, an electron-equilibrium layer of about 5 mm of Lucite was used over the dosimeters.

Figure 1 shows average dosimeter sensitivity (response per unit exposure) as a function of effective photon energy*, all relative to the sensitivity to cobalt-60 gamma-ray photons. There is a relatively large increase in dosimeter sensitivity at low-photon energies amounting to about 50 percent at 34 keV. As a result of the increase in sensitivity at low photon energies of the LiF dosimeters, the depth-dose data that will be obtained in the survey may not exactly correspond to depth-dose data as measured with ion chambers. This will be of no significance in the envisaged survey, in which the participants will be asked to deliver an absorbed dose to water at one prescribed depth in the Lucite phantom. Nevertheless, in order to investigate the limitations of the present system, we also computed response for a given irradiation level as a function of depth in water from the response as a function of depth in Lucite. The response as a function of depth in Lucite was measured by maintaining the distance between the source and the detector at 1 meter and changing the depth of the dosimeters inside the phantom. For all irradiations, the beam cross section in the plane of the dosimeters was 10 cm x 10 cm. Dosimeter readings were related to absorbed dose to water at the same location, utilizing source-standardization data derived from absorbed-dose calorimetry in the same beam for the same field size and distance. The depth in water (t_{water}) equivalent to a given depth in Lucite (t_{Lucite}) was computed as

$$t_{\text{water}} = t_{\text{Lucite}} \left(\frac{\bar{Z}/A}{\bar{Z}/A} \right)_{\text{Lucite}} / \left(\frac{\bar{Z}/A}{\bar{Z}/A} \right)_{\text{water}} \quad (1)$$

where $(\bar{Z}/A)$ stands for the average of the quotient of atomic number and atomic weight here taken for Lucite and water, respectively, as indicated by the subscripts. The depth, t_{water} , computed in this way is the depth

* Effective energy is here defined as the energy of a monoenergetic photon beam associated with the total (narrow-beam) attenuation coefficient obtained from the attenuation curve of the photon beam in question in a suitable absorber (for example, Al or Cu), extrapolated to zero absorber thickness.

Fig. 2 Comparison, Absorbed Dose to Water and Dosimeter Response in Lucite, for Irradiation with Cobalt-60 Gamma Rays, as a Function of Depth in Water. The field size was 10 cm x 10 cm at each depth of measurement. The error bars represent the standard deviation (0.5 to 0.9%) of the response of the nine dosimeters irradiated at each depth. The solid line represents calorimetric depth-dose data in water obtained in the same geometry with the same cobalt-60 gamma-ray sources. The response curve was fitted to the absorbed-dose curve at a depth of 5 cm in water (arrow).

at which the percent depth dose in water is the same as the percent depth dose at the depth, t_{Lucite} , in Lucite.⁸ Figure 2 shows the results. The dosimeter readings were arbitrarily fitted at a depth of 5 cm, but could be fitted at any other depth, just as well. The results indicate that, at least for the spectrum emitted by the cobalt-60 gamma-ray source used for this experiment, the difference in slope of the response-versus-depth and the depth-dose curves is relatively small and results in a slight increase in response per unit of absorbed dose with increasing phantom depth (i.e., for lower photon energies).

Fading of LiF (TLD-100) Response Under Laboratory Conditions

This experiment was carried out for storage in the dark, at temperatures between 18° and 22°C and at relative humidities of less than 45 percent. Tests over a wide range of temperatures and relative humidities were not considered necessary since fading for the annealing methods employed is known to be relatively small for any ambient conditions and possible effects due to variations in ambient conditions thus would be within the measurement uncertainty. Furthermore, BRH has employed the system for postal surveys for several years, without experiencing any difficulties due to variations in ambient conditions.

Figure 3 shows the results of the study, which covers storage periods between irradiation and readout in the range from about 3 to 24 days at three cobalt-60 gamma irradiation levels (0.1, 1.0, and 2.0 Gy). The

Fig. 3 Fading of Dosimeter Response for Three Different Absorbed-Dose Levels. Plotted is response per unit of absorbed dose, corrected for supra-linearity. Circles: 10-rad level; Squares: 100-rad level; Triangles: 200-rad level. All data were normalized to the three-day value for the respective absorbed-dose level.

response data were arbitrarily normalized to the three-day response points. Since the amount of fading was shown not to be a function of irradiation level, a least-squares fit regression line (see formula in fig. 3) was fitted to all the data points obtained for the period from 3 to 24 days between irradiation and readout. Over this period, fading is seen to amount to about 2½ percent.

Influence of Size of Lucite Phantom on Dosimeter Response for the Spectra of Interest

In order to determine if it would be feasible to use for the survey a phantom smaller than the standard phantom cube with sides of 30 cm in length, a study was carried out with smaller cubes. Cubes with sides 15 cm and 20 cm in length loaded at three and four depths, respectively, were irradiated with cobalt-60 gamma radiation and with 10-MV bremsstrahlung. The results of the experiments are shown in table 1. Listed is the response for a fixed irradiation level averaged over the values for nine dosimeters irradiated simultaneously at the particular depths in the two phantoms and radiation beams. The field size was 10 cm x 10 cm in the plane of each measurement. The data reveal a slight trend for responses in the larger phantom to be somewhat higher than those in the smaller phantom, for irradiation with either radiation beam. Since this trend, if significant, would be negligible in the envisaged survey, we decided to dispense with tests employing a phantom cube with 30-cm side length and tests employing 4- and 6-MV bremsstrahlung and concluded that it would be safe to use a phantom cube with sides 15 cm in length for the survey.

Influence on LiF (TLD-100) Response at a Given Phantom Depth in the Presence of Dosimeters in Several Other Depths

BRH had expressed an interest in designing the survey in such a way as to obtain some information on depth-dose data from the various participating insti-

Table 1. Influence of Phantom Size on Dosimeter Response
Field: 10 cm x 10 cm in plane of measurement

Nominal depth in phantom cm	AVERAGE DOSIMETER RESPONSE			
	Cobalt-60 gamma rays in cubic phantom with		10-MV bremsstrahlung in cubic phantom with	
	15 cm sides	20 cm sides	15 cm sides	20 cm sides
2.5	1.001 ± 0.003	0.999 ± 0.005	0.998 ± 0.006	1.002 ± 0.008
5	0.853 ± 0.003	0.860 ± 0.002	0.896 ± 0.004	0.894 ± 0.007
10	0.591 ± 0.004	0.601 ± 0.004	0.682 ± 0.004	0.685 ± 0.005
15	—	0.404 ± 0.002	—	0.522 ± 0.003

* Note that this finding agrees with earlier depth-dose measurements with ion chambers in graphite phantoms made by J. Pruitt and S. Domen of our laboratory, who found a difference of 0.7 percent at a 10-cm depth.

tutions. If possible, this information should be obtained from the results of one single irradiation of the phantom, loaded with dosimeters at different depths along the central phantom axis. In order to ascertain the feasibility of such a procedure, we investigated whether simultaneous phantom loading at different depths influences dosimeter response to the different radiation beams under consideration. Table 2 gives the results of this investigation. Shown is average response of nine dosimeters at a nominal depth of 10 cm in the phantom, in the presence and in the absence of dosimeters at other depths, and the relative standard deviations of these averages. Because of a BRH decision to use phantom cubes with 20-cm sides in their survey, we did not obtain data with all types of radiation for the other phantom sizes.

The data shown in the table reveal a slight trend of questionable significance (i.e., a trend within the limits of the reproducibility of the experiment) for the presence of dosimeters at other depths to decrease the response of the dosimeters at the 10-cm depth—at least for cobalt-60 gamma radiation and 4-MV bremsstrahlung. Nevertheless, it is safe to conclude that the BRH plan to load the mailing phantoms in several depths beyond the peak of the depth-dose curve is entirely feasible. In fact, the work reported below was performed in a cubic phantom with 20-cm sides, loaded with dosimeters at nominal depths of 2.5 cm, 5 cm, 10 cm and 15 cm. The field was 10 cm x 10 cm at a depth of 10 cm.

LiF (TLD-100) Response at a 10-cm Depth in the Lucite Phantom for Irradiation with Cobalt-60 Gamma Radiation and with High-Energy Bremsstrahlung

The cobalt-60 gamma irradiations were performed with one of the NBS standardized sources. Irradiations with high-energy bremsstrahlung were done with accelerators both at the Radiation Oncology Department of the National Cancer Institute and at the Radiation Therapy Department of George Washington University Hospital. At the National Cancer Institute, the two Siemens Mevatrons were used at 6 MV and one of them also at 10 MV after its conversion to a Mevatron-XII. At George Washington University Hospital, we used the Clinac-4 and the Clinac-18, at 4 MV and 10 MV, respectively. The source-to-detector distance was 100 cm for all but the 4-MV high-energy bremsstrahlung beam, where it was 80 cm.

Fig. 4 Typical Dosimeter Response as a Function of Absorbed Dose. Dashed line--linear relationship between response and absorbed dose.

Absorbed dose for the high-energy bremsstrahlung irradiations was obtained by determining initially the reading of a NBS-calibrated Farmer chamber and later the reading of a special NBS graphite chamber at a 10-cm depth in a water phantom cube with sides 30 cm in length and converting the reading to absorbed dose to water by multiplying with the appropriate C_{λ} factor as given in ICRU Report 24⁹, where it is designated by the symbol F . (The factor is 0.94 for 4 and 6 MV and 0.93 for 10 MV.) For the cobalt-60 irradiations, absorbed dose to water was obtained by

Table 2. Influence on Dosimeter Response of the Presence of Dosimeters in Other Depths

TYPE OF RADIATION	AVERAGE DOSIMETER RESPONSE FOR DOSIMETERS AT A 10-cm DEPTH IN					
	Cube, 15 cm sides, with dosimeters at		Cube, 20 cm sides with dosimeters at		Parallelepiped, 15 cm x 15 cm x 20 cm deep with dosimeters at	
	10-cm depth only	2.5-, 5- and 10-cm depths	10-cm depth only	2.5-, 5-, 10- and 15-cm depths	10-cm depth only	2.5-, 5-, 10- and 15-cm depths
Cobalt-60 gamma rad.	0.581 ± 0.002	0.578 ± 0.004	0.589 ± 0.003	0.588 ± 0.004	—	—
4 MV bremsstr.	—	—	0.607 ± 0.003	0.601 ± 0.004	—	—
6 MV bremsstr.	—	—	0.552 ± 0.003	0.552 ± 0.003	—	—
10 MV bremsstr.	0.681 ± 0.003	0.680 ± 0.004	0.685 ± 0.004	0.683 ± 0.005	0.683 ± 0.004	0.685 ± 0.003

Fig. 5 Increase in Dosimeter Sensitivity with Irradiation Level for Irradiation with Cobalt-60 Gamma Radiation and High-Energy Bremsstrahlung. The regression line drawn is for cobalt-60 gamma radiation. The points for the 4-, 6- and 10-MV bremsstrahlung are shown relative to the cobalt-60 gamma-ray regression line, which was made to approach unity as absorbed dose approaches zero.

using results from earlier measurements at the same location with the standard graphite calorimeter.

LiF (TLD-100) response as a function of irradiation level is shown in fig. 4. Typical data obtained for the average response of sets of nine dosimeters irradiated with high-energy bremsstrahlung and with cobalt-60 gamma radiation at a nominal depth of 10 cm, are plotted as a function of absorbed dose to water at the same depth. Dosimeter response is seen to be supralinear, even at relatively low dose levels. Quantitatively, this supralinearity is shown better in figure 5, where sensitivity (response/absorbed dose) is plotted as a function of absorbed dose, normalized for all irradiation conditions at the zero absorbed-dose level. The difference in the slope of the regression lines obtained by least-squares fitting for the different photon spectra is only marginally significant since, in addition to the uncertainty in the fits indicated in figure 5, one must consider an experimental uncertainty of at least 1 percent.* As a consequence, no supralinearity correction is required for a comparison between high-energy bremsstrahlung response of the dosimeters and response to cobalt-60 gamma radiation, at least not at irradiation levels in the vicinity of 1.0 Gy.

LiF (TLD-100) response at a given irradiation level to high-energy bremsstrahlung relative to that to cobalt-60 gamma radiation is shown in table 3. Two series of values for the quotient, $Q(E)$, which is defined as (dosimeter response in Lucite to high-energy bremsstrahlung) / (dosimeter response in Lucite to cobalt-60 gamma radiation for identical levels of absorbed-dose to water). The first series is based on experiments performed over a period of several months. For the high-energy bremsstrahlung, absorbed dose to water at a 10-cm depth in a water phantom was determined from readings of Farmer ionization chambers, with a random reading uncertainty of about 0.3 percent. The irradiations for the second series were all completed within a period of two days and all readouts were done in one sitting. For the high-energy bremsstrahlung, absorbed dose to water was determined from readings of a special NBS graphite ionization chamber, with a

* It is not too surprising that the difference is not large, even in the light of the known dependence of supralinearity on LET^{10,11} since it may be expected that at the 10-cm depth at which the dosimeters were irradiated, the spectra had become much more similar.

Fig. 6 Absorbed Dose to Water as a Function of Depth in the Lucite Phantom, Computed from Dosimeter Response. The absorbed dose data were normalized to those obtained at a depth of 10 cm in Lucite (arrows).

random reading uncertainty of about 0.1 percent. Just as could be expected from earlier studies with various configurations of LiF TLD material,¹² no significant trend is observed as a function of initial beam energy and the difference from unity of any one of the quotients is within the total uncertainty of ~2 percent.

Relative Depth Dose in Lucite Phantom Derived from LiF (TLD-100) Response

Figure 6 shows representative depth-dose data for depths of 2.5 cm, 5 cm, 10 cm and 15 cm in Lucite obtained in the study described in the previous sections. Inasmuch as the participants in the BRH survey will be asked to determine absorbed dose to water at a depth of 10 cm in the phantom, all data are plotted relative to the dose at this depth. Analysis of least-squares fits (such as the solid lines shown in the figure) indicate that the method may be sufficiently accurate for obtaining some information on a participant's gross beam energy from survey data at three or four different phantom depths, but that it will be difficult to detect small differences among linear accelerators of the same nominal energy.

Table 3. Quotient, Dosimeter Response in Lucite per Unit of Absorbed Dose to Water at a 10-cm Depth in the Lucite Phantom

Radiation Source	Nominal Peak Energy	Quotient	
		Series 1	Series 2
Varian Clinac-4 (George Washington U. Hosp.)	4 MeV	1.01 ²	0.99 ¹
Siemens Mevatron VI (a) (National Cancer Institute)	6 MeV	1.02 ²	—
Siemens Mevatron VI (National Cancer Institute)	6 MeV	1.01 ³	1.00 ¹
Varian Clinac-18 (George Washington U. Hosp.)	10 MeV	0.99 ⁴	0.97 ⁹
Siemens Mevatron XII (b) (National Cancer Institute)	10 MeV	0.97 ⁷	1.00 ⁰
		Average:	
		1.004 +0.019 -0.027	0.993 +0.008 -0.014

(a) Before conversion to Mevatron XII (see 10-MeV points obtained at the National Cancer Institute).

(b) After conversion from Mevatron VI.

Dependence of LiF (TLD-100) Sensitivity on Irradiation History

The experiments described were all carried out with the same set of 100 dosimeters. During these experiments, we observed that dosimeter response to the constant test irradiations of ~ 5 R of cobalt-60 gamma radiation decreased monotonically with dosimeter use at the test-irradiation levels. When an experiment involving irradiation levels of ~ 1 Gy or more was carried out between any two test irradiations, this pattern was interrupted, the glow curves for the test irradiations following the experiment reflecting electron release from traps deeper than those filled at the lower irradiation levels, a release that tended to disappear only after several annealing and use cycles. Figure 7 shows the resulting behavior of the 100 dosimeters throughout 35 irradiation and annealing cycles. The data points indicate the average response of these dosimeters to the constant test irradiations. Where experiments involving the irradiation of some of the dosimeters followed by readout and annealing of all the dosimeters were performed between any two test irradiations, the types and levels of the intervening irradiations are indicated.

The solid straight line represents a least-squares fit to the test-data points, indicating an overall loss in dosimeter sensitivity of ~ 9 percent after the 35 irradiation and annealing cycles. The dashed line is a fit to the first six data points for test cycles done in succession without intervening experiment runs. The decrease in sensitivity is seen to be larger, amounting to almost 2 percent after these six cycles, i.e., to ~ 0.3 percent per test cycle.

In order to study the behavior of the dosimeters after irradiation at levels higher than the ~ 5 -R test level, the change in the response to the test irradiation is plotted in figure 8 for the average readings of a group of nine dosimeters irradiated simultaneously. The points again are for the response to the test irradiations. Where experiment cycles were interspersed, the irradiation types and levels are indicated. Note that a 4.0-Gy irradiation causes a sensitivity increase of ~ 8 percent, followed by a decrease in sensitivity of ~ 3 percent per subsequent test cycle.

Results of Pilot Comparison Study

The Radiation Physics Department of the Massachusetts General Hospital (MGH) was selected for this pilot study because it had been a participant a few weeks earlier in an IAEA pilot comparison study with the Harvard School of Medicine. At the time of the NBS-MGH study, the decision had not been made as yet to ask for delivery of 1.0 Gy to water at a 10-cm depth in Lucite. For the NBS-MGH study, we asked MGH to administer to our phantom (a Lucite cube with 20-cm side length, loaded with 9 dosimeters each in the depths of 2.5 cm, 5 cm, 10 cm, and 15 cm) an absorbed dose from their 10-MV bremsstrahlung beam (Clinac-18) corresponding to 2.0 Gy to water. The dose was to be delivered at a depth in Lucite of 5 cm, using a 10 cm x 10 cm field size at this depth. We computed the absorbed dose to water from a cobalt-60 source that corresponded to the response in Lucite measured with the dosimeters that had been irradiated at MGH in the 10-MV bremsstrahlung beam. We arrived at the absorbed dose to Lucite (D_{Lucite}) from the absorbed dose to water as measured by the NBS standard absorbed-dose calorimeter as

$$\begin{aligned} D_{\text{Lucite}} \mu_0(\text{Lucite}) t_{\text{Lucite}} &= \\ &= D_{\text{water}} \mu_0(\text{water}) t_{\text{water}} \frac{\mu_{\text{en}}^{\text{Lucite}}}{\mu_{\text{en}}^{\text{water}}} \quad (2) \end{aligned}$$

where the μ_0 symbols stand for the mass attenuation

Fig. 7 Change in Dosimeter Sensitivity with Irradiation History. Average response of 100 dosimeters to a constant test irradiation is plotted. Types and levels of intervening irradiations on some of these dosimeters are indicated.

coefficients for the incident spectrum for Lucite and water; $\mu_{\text{en}}^{\text{Lucite}}$ is the quotient of the average mass energy absorption coefficient for Lucite and for water, taken at a depth in water, $t_{\text{water}} = 5$ cm, and the corresponding depth, t_{Lucite} , computed by eq. (1).

Since, for our cobalt-60 gamma-radiation source, 5 cm of a low-Z material represents only a fraction of one mean-free path and μ_{en} is essentially constant over

the energy range represented, μ_{en} values for the

incident beam were used in the computation of $\mu_{\text{en}}^{\text{Lucite}} / \mu_{\text{en}}^{\text{water}}$.

A similar computation was performed for the 10-MV bremsstrahlung beam. Equation (2) was again used to determine the relationship between absorbed dose to Lucite at a 5-cm depth in Lucite and absorbed dose to water at the corresponding depth in water. However, since $\mu_{\text{en}}^{\text{Lucite}} / \mu_{\text{en}}^{\text{water}}$ changes by about 2 to 3 percent between

Fig. 8 Change in Dosimeter Sensitivity with Irradiation History. Average response of 9 dosimeters to a constant test irradiation is plotted. Types and levels of intervening identical irradiation on all 9 dosimeters are indicated.

1 and 10 MeV, an average value, $\bar{\mu}_{\text{en, water}}^{\text{Lucite}}$, was computed

under the assumption of a triangular bremsstrahlung spectral distribution filtered by 1.9 cm of tungsten, which, according to Varian Associates, is the filtration in a 10-MV Clinac-18 beam.⁴ The resulting value for the interpretation of the dosimeter readings in Lucite at 10 MV in terms of cobalt-60 gamma-ray absorbed dose to water was 1.996 Gy, while the value quoted by MGH was 2.018 Gy. This led to a value of 1.011 for the quotient of the dose assigned by MGH and the NBS dose interpretation in terms of NBS cobalt-60 gamma rays. The corresponding quotient in the MGH-IAEA comparison was quoted to us by the IAEA and the Harvard Medical School as having been 1.014. This difference is well within the uncertainty limits of the IAEA and the NBS pilot studies.

Another result concerned the slope of the dosimeter response-versus-depth curve obtained with the 10-MV Clinac-18 at MGH, which was about 1-percent smaller than the slope we obtained at 10 MV both with the Mevatron XII at NCI and the Clinac-18 at GWU Hospital. Considering that the geometries were not quite comparable (10 cm x 10 cm field size at a 10-cm depth at NCI and at GWU Hospital, at a 5-cm depth at MGH), this agreement is also satisfactory.

Discussion of the Magnitude of the Uncertainty Expected for the Planned Survey for Individually and Batch-Calibrated Dosimeters

It is envisioned that the survey protocol will require that the participants be furnished a Lucite phantom loaded with LiF (TLD-100) dosimeters from a batch in which TLD sensitivity had been characterized either for each individual dosimeter or for the batch as a whole. The participants will be asked to deliver a prescribed absorbed dose to water (say, 1.0 Gy) to a point at a 10-cm depth in the phantom, computing the dose as if the phantom material had been water. At the same time, TL dosimeters from the same batch will be irradiated by BRH with cobalt-60 gamma radiation from one of the standardized NBS sources at suitable calibration levels, in a similar phantom. BRH then will compute the high-energy bremsstrahlung absorbed dose to water delivered by the participant ($D_{\text{partic.}}$) at a 10-cm depth in the water phantom from the average dosimeter response of the dosimeters irradiated by the participant ($r_{\text{partic.}}$) at a 10-cm depth in the Lucite phantom as

$$D_{\text{partic.}} = r_{\text{partic.}} (D/r)_{\text{BRH}} Q(E), \quad (3)$$

where $(D/r)_{\text{BRH}}$ is the quotient of absorbed dose over TLD response at a 10-cm depth in the Lucite phantom, as obtained from the current BRH cobalt-60 gamma-ray calibration curve, and the quotient $Q(E)$ is given in table 3 for the various nominal peak energies. The uncertainty inherent in the survey procedure contains the uncertainties in each of the factors of eq. (3). In practice, it may become necessary to consider also the uncertainty in a fading correction factor which may have to be added to eq. (3) if the BRH calibration irradiations with the NBS cobalt-60 gamma-ray source are not going to be administered at approximately the same time as the high-energy bremsstrahlung irradiations at the participating laboratories. Not included in the considerations of uncertainty were the systematic uncertainties common to surveyor and surveyed, which are inherent in the cobalt-60 gamma-ray calibration of the ion chamber and in the factor C_1 , both used in the determination of absorbed dose to water in the high-energy bremsstrahlung beam.

It is estimated that, in the envisaged survey procedure, a minimum random uncertainty of ~1.5 percent is associated with batch-calibrated dosimeters, as compared

to ~1 percent for individually calibrated dosimeters; the corresponding overall uncertainty in the dose interpretation from the readings on nine identically irradiated dosimeters is ~4 percent for batch-calibrated dosimeters and ~3 percent for individually calibrated dosimeters.

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