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Uniformity of High-Energy Electron-Beam Calibrations

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ABSTRACT. A survey is made of the first year of operation of a new service offered by the National Bureau of Standards (NBS). Dosemeter units, consisting of polystyrene blocks holding stoppered quartz spectrophotometer cells filled with Fricke solution, are being shipped periodically to groups requesting assistance with absorbed-dose measurements in high-energy electron beams. As a check on their stability, all dosemeters are pre-exposed to ^{60}Co γ-rays. The participants irradiate a portion of the dosemeters with electrons, using energies between about 5 and 50 Mev, and doses between 4000 and 8000 rads in water. The exposed dosemeters are returned to NBS for evaluation. During the first year of operation, slightly more than one-half of the doses reported by the participants were within $\pm 5\%$ of the NBS dose interpretation, but some differed by as much as 30% or more. Little correlation was found between a participant's method of beam calibration and agreement with NBS dose interpretation.

1. Introduction

Since July 1967 the National Bureau of Standards (NBS) has been mailing Fricke dosemeter units quarterly to groups in the United States requesting assistance with absorbed-dose measurements in high-energy electron beams (Lanzl 1967; Department of Commerce 1967). This service is thought of as a stop-gap procedure, to be carried out while the NBS standard absorbed-dose calorimetry programme is under development.

In this paper, the information which NBS collected on electron-therapy equipment and procedures is surveyed briefly; material is presented on NBS's experience in the preparation, shipping and evaluation of large numbers of Fricke dosemeters; and finally, representative data and observations are given on the results obtained during the first year of the service regarding the uniformity of high-energy electron-beam calibrations for radiation therapy.

2. Survey of equipment and procedures employed by participants in NBS studies

Table 1 shows a summary of the types of electron machines used by the participants in the NBS studies, and the methods of beam broadening, monitoring and calibration. For coverage of the required treatment area, the initially narrow, monoenergetic electron beams from betatrons or linear accelerators, operating at energies between 5 and 33 Mev, usually are broadened by means of thin scattering foils of low atomic number. One institution employs a narrow, monoenergetic beam of electrons, and scans the treatment

Table 1. Summary of survey results[1]

Item	No. of participants using the item
1. Type of Accelerator	
betatron	12
linear accelerator	4
2. Field Coverage by	
scanning	1
beam broadening through scattering	15
3. Range of Electron Energies (T)[2]	
$5 \leqslant T < 10$	6
$10 \leqslant T < 15$	7
$15 \leqslant T < 20$	11
$20 \leqslant T < 25$	6
$25 \leqslant T < 30$	3
$30 \leqslant T \leqslant 35$	3
4. Scatterer (or Scanner)-to-Phantom Distance (d)	
$d <$ 50 cm	4
50 cm $\leqslant d <$ 100 cm	7
$d =$ 100 cm	3
100 cm $< d <$ 150 cm	1
5. Cone Material	
aluminium	3
brass	1
steel	4
lead	3
aluminium-brass-combination	1
6. Collimating Diaphragm Material	
graphite	1
aluminium	3
brass	1
steel	1
lead	2
aluminium-steel-lead-steel combination	1
7. Accelerator-Tube Window Material	
beryllium	7
aluminium	1
plastic	1
glass	1
ceramic	3
nickel	1
8. Scattering, Foil Material[3] and Thickness	
aluminium (0·03)†	4; $5 \leqslant T \leqslant 20$ Mev
nickel (0·008)	1; $T = 6$ Mev
stainless steel (0·005)	1; $T = 8$ Mev
copper (0·010–0·014)	2; $15 \leqslant T \leqslant 35$ Mev
lead (0·010–0·024)	4; $15 \leqslant T \leqslant 22$ Mev
aluminium (0·03)+lead (0·01)	6; $8 \leqslant T \leqslant 25$ Mev
copper (0·01)+lead (0·013)	1; $T = 33$ Mev
9. Monitor	
transmission ion chamber	12
cavity chamber	3
10. Beam Calibration[4]	
(*a*) absorbed-dose calorimeter	
at participant's institution	2
elsewhere (indirect calibration)	3
(*b*) Fricke dosemeter (G=15·5 or 15·6/100 ev)	
at participant's institution	2
elsewhere (indirect calibration)	2
(*c*) Faraday cage; absorbed dose computed from flux density	1
(*d*) various ionization chambers[5]	
calibrated against (*a*) or (*b*)	6
without correction	4
(*e*) thermoluminescence dosemeters[6]	2

† The numbers in the parentheses are thicknesses in inches, most of them as supplied by the participants.

[1] Not all participants responded, and not all of those responding answered all questions.
[2] All but a few participants used more than one energy.
[3] For some, the accelerator tube window acted as the scatterer.
[4] Some participants used more than one method.
[5] Siemens, Victoreen, and Baldwin–Farmer.
[6] Calibrated with ^{60}Co γ-rays in terms of absorbed dose in polystyrene.

area. There is considerable variation in the physical facilities (type of accelerator; materials used for beam window, collimator, and cone; scatterer-to phantom-distance). To calibrate their beams, several groups use absorbed-dose calorimetry (either directly or indirectly via measurements with another instrument, for example, an ionization chamber calibrated against an absorbed-dose calorimeter), or Fricke dosimetry. Others use ionization chambers or LiF thermoluminescence dosemeters calibrated with ^{60}Co γ-rays in terms of absorbed dose in a phantom, and apply correction factors relating the response of their dosemeter to ^{60}Co γ-rays and to high-energy electrons. Still others employ ionization chambers calibrated with ^{60}Co γ-rays in terms of exposure, placing them in the phantom used for electron irradiation, and—ignoring conceptual and other difficulties—taking their readings (in R) in the electron beam as the absorbed dose in the medium. Many groups employ more than one method.

3. The NBS Fricke Dosemeter

3.1. *Preparation*

Fricke solution, prepared according to the guidelines of the American Society for Testing Materials (ASTM Standards 1965), is used in silica cells which, in turn, are cradled in polystyrene blocks. The units are shown in fig. 1. The glass-stoppered silica spectrophotometer cells were chosen because of their resistance to radiation damage, and because the use of plastic containers would

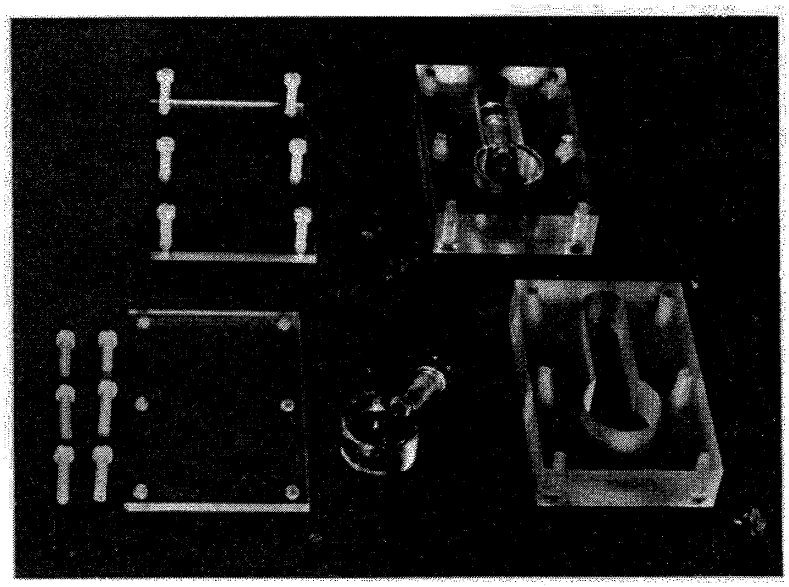

Fig. 1. Fricke dosemeter units. The spectrophotometer cell fits snugly into the polystyrene block; in the finished assembly, a styrofoam plug presses against the stopper, and keeps it in place.

result in organic contamination of the solution. Under the present arrangement, handling time and sources of contamination are further reduced by keeping the Fricke solution in the stoppered cell throughout the entire process of testing, irradiation, and evaluation.

The polystyrene block is machined to fit into a recess in the polystyrene phantom recommended by the Sub-committee on Radiation Dosimetry (SCRAD) of the American Association of Physicists in Medicine (1966). The centre of the unit is at 1 cm below the surface, which is the depth recommended by SCRAD for use at the lowest electron energy employed for therapy, i.e. 5 Mev.

Prior to their first use, all cells are cleaned ultrasonically in a 0·8 N sulphuric-acid bath. Distilled and de-ionized sterile water from a commercial supplier is employed for the preparation of the Fricke solution and all cleansing procedures. A comparison of the performance of dosemeters prepared with this and with triply distilled water showed no difference in the stability and reproducibility of their densities (Pinkerton 1967). It was determined previously (Pinkerton, private communication from Memorial Hospital, New York) that, for electrons of 6 Mev and above, and for Fricke solution irradiated in a polystyrene phantom, the densities obtained with polystyrene irradiation cells agree to within the experimental reproducibility (better than 1%) with the densities obtained with quartz irradiation cells (1 mm wall thickness) for the same pathlength of solution, and the same average absorbed dose.

The cells are rinsed several times with the sterile water and the Fricke solution before the final filling is made. Because of the narrow cell necks which help

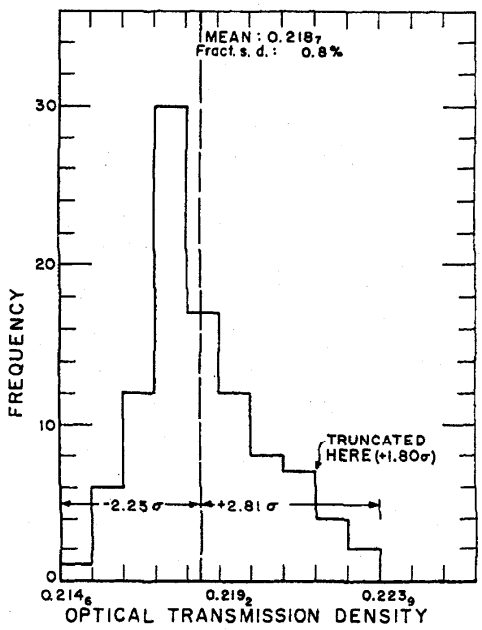

Fig. 2. Statistical distribution of densities after pre-exposure to ^{60}Co γ-rays.

prevent spilling during shipment, but also make cleaning more difficult, the cells are emptied by aspiration and by shaking. Wash water and solution are transferred to the cells from wash bottles equipped with finely drawn-out glass spouts and pressure balloons. Glass tubing is used in all parts of the system that come in contact with these liquids.

3.2. *Test exposures*

After an initial sampling of the optical transmission density (hereafter called density) of the unexposed dosemeters, all dosemeters are exposed identically to ^{60}Co γ-rays to a density of between 0·20 and 0·25, corresponding to a dose of between 5000 and 6000 rads in water. An example of the resulting statistical distribution of the densities is shown in fig. 2. Typically, the distribution is somewhat skewed toward the higher densities. Its fractional standard deviation is slightly below 1%. In an attempt to eliminate possible unstable dosemeter cells whose densities were considerably higher than average, the

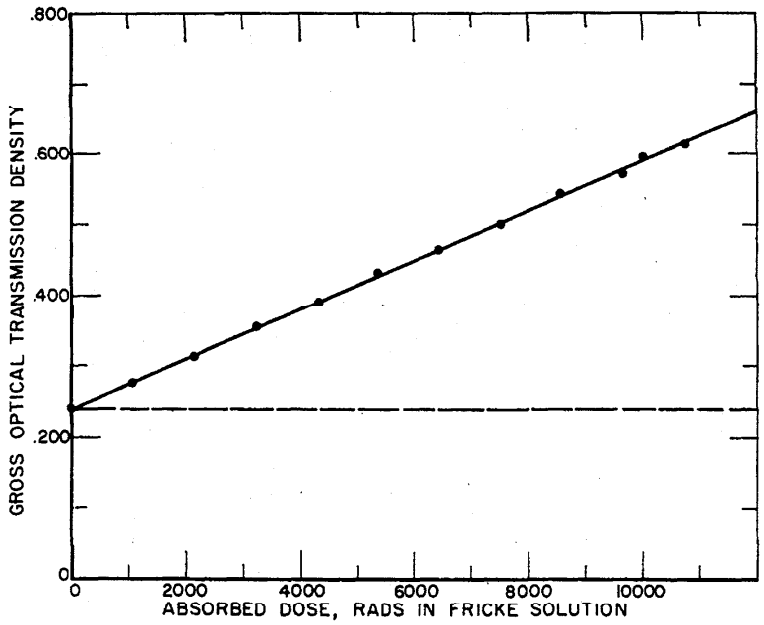

Fig. 3. Result of a test of the additivity of the response to ^{60}Co γ-rays and to high-energy electrons. The absorbed dose values plotted as abscissae are those determined by the Therapy Department of Michael Reese Hospital, Chicago, for their 33 Mev electron irradiations. The density values plotted as ordinates were obtained at NBS. The solid line through the points was obtained by a least-squares fit of the data. The dashed line represents the density level due to the initial ^{60}Co γ-ray exposures.

distribution was truncated arbitrarily, and all further work was done with the pre-exposed dosemeters whose densities were within the truncated distribution.†

A question may arise regarding the justification for using dosemeters pre-exposed to ^{60}Co γ-rays for subsequent work with high-energy electrons, particularly since the G-value of the Fricke solution may be different for the two types of radiation. Fig. 3 shows the result of a test of the additivity of the response to ^{60}Co γ-rays and to high-energy electrons for one group of Fricke dosemeters. All samples were first irradiated identically with ^{60}Co γ-rays to produce a density of about 0·24; subsequently, they were given a series of 33 Mev electron doses between 1000 and 11 000 rads in water. The G-value computed from the slope of the density-versus-electron-dose curve agreed within 1·3% with the G-value used initially to compute the absorbed dose.

3.3. *Spectrophotometry*

All densities were determined with a commercial spectrophotometer provided with a hydrogen lamp, a temperature stabilizer, and a digital read-out. The readings were carried out at 25°C, at a wavelength of 304 nm. The spectrophotometer was calibrated over the range of densities of interest with ferric-ion solutions of known molarity, made with pure iron dissolved in 0·4 M sulphuric acid, oxidized with hydrogen peroxide, and then heated to drive off excess hydrogen peroxide. The molar extinction coefficient for a given ferric-ion concentration, determined for successive calibrations of this type, is estimated to be known to within 0·1%. However, with the particular spectrophotometer used, its value depends on ferric-ion concentration, and thus on density. The change over the density range of interest (a range of about 0·22 to 0·63) is approximately 0·9% (from about 2179/mole cm to about 2160/mole cm).

4. The NBS uniformity studies

4.1. *Electron irradiation by participants*

The participants are asked to expose all but two of the furnished dosemeters to between 5000 and 8000 rads in water, at electron energies between 5 and 50 Mev, employing the exposure geometry (field size, type of phantom, position of dosemeter in phantom) recommended by SCRAD. After irradiation, the dosemeters are returned to NBS for spectrophotometric evaluation of the ferric-ion concentration in terms of the absorbed dose in the dosemeter solution.

4.2. *Evaluation of the participants' performance*

After return of the mailed dosemeter units, all dosemeters are read again, and the net density of the electron-exposed dosemeters is determined as the difference between their measured densities and the mean density of the control-dosemeter cells. An experiment was performed on one batch of Fricke solution in order to determine whether density growth with time under varying

† For the sample distribution shown in fig. 2, it later turned out that, over a period of one month, none of the eliminated dosemeters showed an excessive drift in density.

storage conditions is a function of density level. No significant trend was observed between shipped samples and samples remaining at NBS. During the period of about four weeks between the first and second spectrophotometer readings, the average density of the control dosemeters increases by about 0·003 to 0·004. Typically, there is little difference between the standard deviations for the shipped controls and those remaining at NBS, but the distribution for the shipped controls usually is more symmetrical.

The NBS Fricke-dosimetry service is intended as an aid to other laboratories for achieving uniformity in the calibration of high-energy electron beams. A reference to absorbed dose is, therefore, not required in the NBS evaluation of the test results. However, it was felt that such a reference would be helpful. It was decided to provide an interpretation of the results in terms of absorbed dose, with the understanding that the NBS dose values will not be based on an absolute calibration procedure, but will be obtained with the aid of certain assumptions about the G-value (see below). The absorbed dose in the Fricke dosemeters was determined as

$$D_{\text{Fricke}} = (0{\cdot}942_6 \times 10^9 \times \text{net density})/(\epsilon_{\text{Fe}}{}^{+++} - \epsilon_{\text{Fe}}{}^{++})G,$$

where the constant is the product of Avogadro's number and the conversion factor from ev to rads, divided by the specific gravity of the solution; $\epsilon_{\text{Fe}}{}^{+++}$ is the molar extinction coefficient for ferric ions, determined experimentally for the particular spectrophotometer and the particular conditions of its use (see section 3.3); and $\epsilon_{\text{Fe}}{}^{++}$ is the molar extinction coefficient for ferrous ions, which was set equal to unity. The G-value was assumed to be independent of temperature over the range encountered during irradiation of the dosemeters under laboratory conditions, and to be equal to 15·5/100 ev over the electron-energy range of interest.† Also, within the limits of uncertainty of the NBS Fricke-dosimetry service, it was assumed that the dose in the Fricke-dosemeter solution could be set equal to that in water. The absorbed dose per unit fluence for the Fricke solution is only a few tenths of 1% higher than that for water (Pettersson and Hettinger 1967).

In order to test our ability to interpret the participants' irradiations, we carried out a test involving exposure at NBS of Fricke dosemeters to two levels of ^{60}Co γ-rays, mailing them to a number of participants who then returned them for evaluation. The rms value of the difference between the dose computed from exposure and that determined from readings on an individual Fricke dosemeter was about 1·5%. The corresponding 95% confidence interval for individual dosemeter readings was about 3%.

4.3. *Typical performance*

The typical overall performance of the participants as a group in a single mailing is reflected by fig. 4, in which the dose values reported by each participant

† Pettersson and Hettinger (1967) use a temperature coefficient of +0·15% per °C. For data on the trend of G with LET, see, f.i., ICRU Report 10 b (1964).

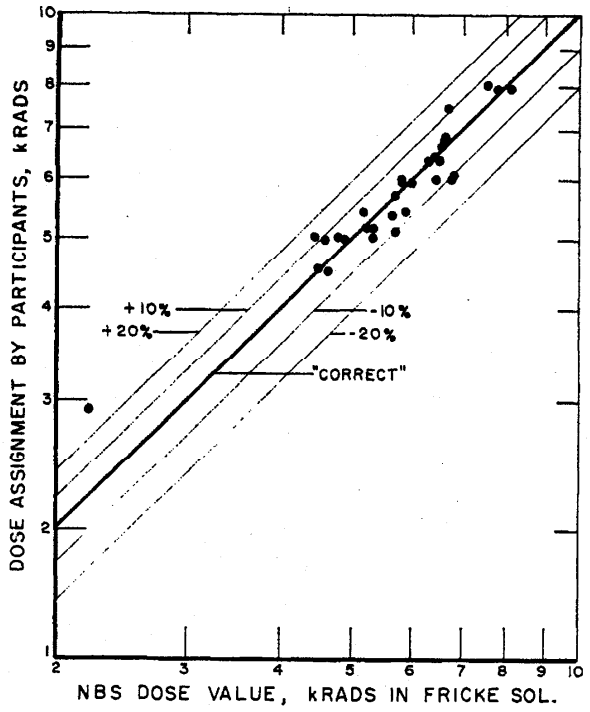

Fig. 4. Overall performance of the participants as a group in a single mailing.

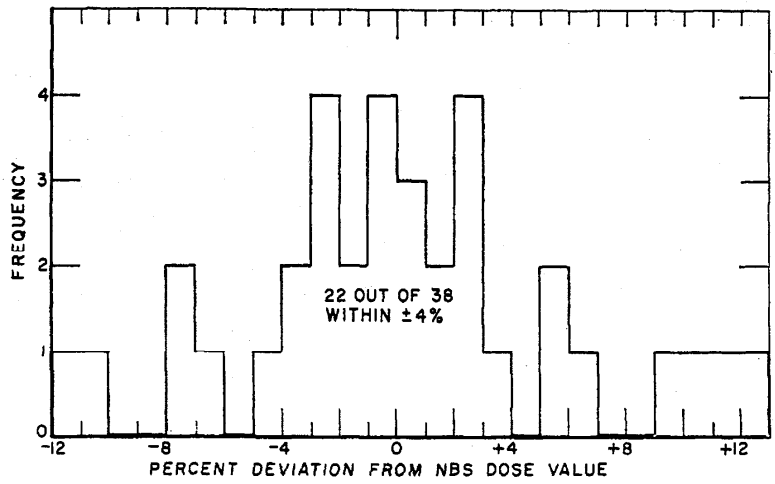

Fig. 5. Statistical evaluation of the dose data shown in fig. 4. Not plotted are three reported dose values that deviated from the NBS dose interpretation by more than +13%.

are plotted on a log–log plot against the values determined at NBS. Along the heavier 45-degree line marked " correct ", the values assigned by the participants agree with the NBS dose interpretation. The other lines are the boundaries of regions in which the deviation from the " correct " values is smaller than the indicated boundary value. Fig. 5 shows the results of a statistical evaluation of the dose data shown in fig. 4. The distribution is slightly skew, indicating that there is a tendency for the dose reported by the participants to be somewhat higher than that determined at NBS. In 22 out of 38 cases, the participants' dose assignment was within $\pm 4\%$ of the NBS dose evaluation.

So far, NBS has carried out four tests. In some instances, the agreement between the doses reported by the participants and the NBS dose interpretation improved with subsequent tests, but not in all. Little or no correlation could be found between the extent of agreement with NBS and the method used for calibrating the electron beam. Nagl and Sanielevici (1967) had similar experiences in their international comparisons.

4.4. *Future work*

In the hope that the NBS Fricke-dosimetry service is contributing to an improvement in the uniformity of therapy dosimetry in the United States, it is planned to continue it, if there is demand, at least up to the time that NBS will be in a position to offer an absorbed-dose calorimetry service.

We wish to thank Dr. Jaques Ovadia and his staff of Michael Reese Hospital, Chicago, for administering the electron irradiations required for the study of additivity of the response of the Fricke-dosemeters to electrons and ^{60}Co γ-ray photons. We also wish to thank Mr. Arthur Pinkerton of the Sloan-Kettering Institute, New York, and Dr. Peter Almond of M.D. Anderson Hospital, Houston, for assisting in the planning of the service, and Mr. Erle Deardorff of NBS for carrying out the spectrophotometer readings.

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RÉSUMÉ

L'uniformité des calibrations avec des faisceaux d'électrons de haute énergie

On rend compte de la première année du fonctionnement d'un service nouveau existant au National Bureau of Standards (NBS). Des dispositifs dosimétriques, composés des blocs polystyrène portant des cuvettes spectrophotométriques en quartz avec bouchon, remplies de la solution Fricke, sont envoyés périodiquement aux groupes qui voudraient être aidés dans les mesures de la dose absorbée en cas de faisceaux d'électrons de haute énergie. Pour contrôler leur stabilité tous les dosimètres sont exposés préalablement aux rayons gamma du ^{60}Co. Les participants irradient une partie de dosimètres avec des électrons, en employant des énergies entre 5 et 50 Mev environ, et des doses entre 4000 et 8000 rads en l'eau. Les dosimètres exposés sont retournés au NBS pour être évalués. Pendant la première année du fonctionnement, un peu plus que la moitié de doses communiquées par les participants ne différait plus que de $\pm 5\%$ de la dose d'interprétation de NBS, mais pour quelques doses la différence s'élevait à 30% ou davantage. On a trouvé peu de corrélation entre la méthode employée par le participant pour la calibration du faisceau et l'accord avec la dose d'interprétation de NBS.

Zusammenfassung

Gleichförmigkeit der Kalibrierung mittels energiereicher Elektronenstrahlen

Es wird eine Übersicht ausgeführt für das erste Arbeitsjahr der vom National Bureau of Standards (NBS) angebotenen Dienstleistungen. Dosimetergeräte bestehend aus Polystyrolblöcken mit einer verschlossenen, mit Frickelösung gefüllten Spektrophotometer-Quartz-Küvette, werden periodisch an Gruppen ausgesandt, welche um Hilfe in Messungen der absorbierten Dosis mit energiereichen Elektronenstrahlen bitten. Als Stabilitätskontrolle were alle Dosimeter zuerst ^{60}Co-Gammastrahlen ausgesetzt. Die Teilnehmer bestrahlen einen Teil dieser Dosimeter mit Elektronen, wobei Energien von ungefähr 5 bis 50 Mev, und Dosen zwischen 4000 und 8000 rad im Wasser angewandt werden. Die bestrahlten Dosimeter werden an das NBS zur Bewertung zurückgesandt. Im Laufe des ersten Arbeitsjahres, etwas mehr als die Hälfte der von den Teilnehmern gemeldeten Dosen waren innerhalb der Grenzen von $\pm 5\%$ von der NBS-Dosis-Deutung verschieden, doch betrug der Unterschied in manchen Fällen 30% oder mehr. Es wurde eine unbedeutende Korrelation gefunden zwischen dem vom Teilnehmer angewandten Strahlen-Kalibrierungsverfahren und der Übereinstimmung mit der NBS-Dosis-Deutung.

Резюме

Единообразие калибровок электронных лучей большой энергии

Представлен отчет первого года существования новой службы, предлагаемой Национальным бюро стандартов (НБС) США. Дозиметрические установки, состоящие из полистироловых блоков с закупоренными кварцевыми спектрофотометрическими кюветами, наполненными раствором Фрикке, отправляются периодически к группам, нуждающимся в содействии при замерах поглощенной дозы в случае электронных лучей большой энергии. Для проверки их стабильности все дозиметры подвергаются предварительно облучению гамма-лучами из ^{60}Co. Участники облучают часть дозиметров электронами, применяя энергии от около 5 до 50 Мэв и дозы между 4000 и 8000 рад в воде. Облученные дозиметры возвращаются в НБС для оценки. В течение первого года работы немногим более половины доз, указанных участниками, находилось в пределах $\pm 5\%$ от интерпретации дозы НБС, но некоторые дозы разнились на 30% или больше. Слабая корреляция была найдена между методом, употребленным участником для калибровки лучей, и согласием с интерпретацией дозы НБС.

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