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FERROUS SULPHATE DOSIMETER FOR CONTROL OF IONIZATION CHAMBER DOSIMETRY OF ELECTRON AND ^{60}Co GAMMA BEAMS

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The calibration and use of plane-parallel ionization chambers for the determination of absorbed dose to water in electron beams were discussed previously (MATTSSON et coll. 1981) and the conclusions were made use of in the recommendations endorsed by the Nordic Association of Clinical Physics (NACP 1981). In the present report the ionization chamber dosimetry, applying NACP (1980) and NACP (1981), was checked against the ferrous sulphate dosimetry. Measurements have been carried out in electron beams in the energy range, $\bar{E}_0$, 2.8 to 27.5 MeV, and in ^{60}Co gamma beams. Both plane-parallel and cylindrical ionization chambers were used as plane-parallel chambers are recommended for electron energies ($\bar{E}_0$) below 15 MeV and cylindrical chambers for higher energies and ^{60}Co gamma beams (NACP 1980, 1981). The measurements in ^{60}Co gamma beams were included as this quality is used for calibration of ionization chambers.

The ferrous sulphate dosimeter was chosen as reference system as the dosimeter solution is nearly water-equivalent for the investigated qualities. If irradiation cells with thin plastic walls are used the ferrous sulphate dosimeter will cause only a very small disturbance of the radiation field inside the phantom. The yield of ferric ions per absorbed dose can be assumed to be almost independent of the electron energy (SVENSSON & BRAHME 1979). A precision in the region of a few tenths of a per cent is achievable with a high performance ferrous sulphate dosimetry system.

Irradiation equipment. The measurements were carried out in electron beams from a Philips SL 75/20 linear accelerator, a Scanditronix MM22 microtron and a Brown-Boveri Asklepitron 35 betatron, and in ^{60}Co gamma beams from a TEM Mobaltron and a Siemens Gammatron 1.

Measurement procedure. Most of the measurements were carried out in a water phantom but in some cases a polystyrene phantom was used. The field size was 12 cm × 12 cm in most electron beam measurements and 10 cm × 10 cm in most ^{60}Co gamma beam measurements. The SSD was in the electron beam measurements 100 cm and in the ^{60}Co gamma beam measurements 80 or 60 cm.

The measurement procedure was as follows: first a measurement was made with the ionization chamber, then ferrous sulphate dosimeters were irradiated, and finally the ionization chamber measurements were repeated. The whole sequence was repeated a number of times for each energy.

Ionization chamber dosimetry

Measurements were made using both cylindrical and plane-parallel ionization chambers. The cylindrical chamber was a Baldwin-Farmer type 2505, having a graphite wall and the plane-parallel cham-

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ber was a NACP chamber (MATTSSON et coll., NACP 1981). The absorbed dose to air calibration factor, $N_{D,cyl}$, for the cylindrical chamber was derived from the exposure calibration factor, N_X, according to NACP (1980). A $k_{att}k_m$-value equal to 0.975 was used (JOHANSSON et coll. 1978). The $N_{D,pp}$ for the plane-parallel chamber was obtained from a comparison with a cylindrical chamber in high energy electron beams as described by MATTSSON et coll. and NACP (1981).

The absorbed dose to water, D_w (NACP 1980, 1981), was calculated from

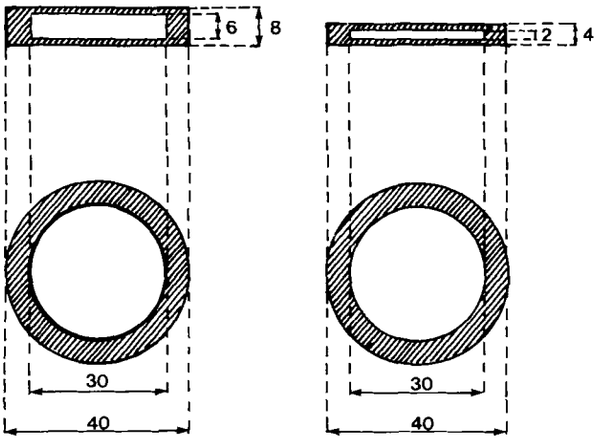
$$D_w = M_u N_D (s_{w,air})_u p_u \quad (1)$$

where M_u is the meter reading, $(s_{w,air})_u$ is the water to air stopping power ratio, and p_u is the perturbation correction factor.

For each electron beam a complete depth ionization curve was measured to determine the input parameters, i.e. the mean energy at the phantom surface ($\bar{E}_0$) and the mean energy at the point of measurement ($\bar{E}_z$), for the choice of $(s_{w,air})_u$ and p_u, respectively. The $(s_{w,air})_u$-values were taken from NACP (1980) above $\bar{E}_0$=15 MeV and from NACP (1981) at and below 15 MeV and the p_u-values for the cylindrical chamber from JOHANSSON et coll. The p_u-values for the plane-parallel chamber were assumed to be unity for electron beams (NACP 1981), and were derived from MATTSSON et coll. for ^{60}Co gamma beams. The numerical values used are given in Tables 2 to 4.

The ferrous sulphate dosimeter system

For the measurement of the ferric ion concentration of the irradiated ferrous sulphate solution a high precision spectrophotometer, type Cary 219 was used. In order to check the absorbance scale of the instrument it was compared in two series of measurements with National Physical Laboratory (NPL), United Kingdom and with Laboratorium voor Kernfysika, Gent University, Belgium. In the first experiment acidic potassium dichromate solutions ($K_2Cr_2O_3$) were prepared by the NPL and brought to Gothenburg. Measurements were made at a wave-length of 313 nm and for absorbances in a 10 mm path-length cell in the range 0.1 to 0.5 ODU. The maximum deviation between the absorbances measured at NPL and in Gothenburg was 0.12 per cent (SHARPE 1979). In the second intercomparison



The ferrous sulphate irradiation cells. Two types of PMMA cells were used having different thicknesses.

the acidic potassium dichromate solutions were prepared in Gothenburg and taken to Gent. Also in this case the agreement was very good being within 0.1 per cent.

In all absorbance measurements calibrated semi-micro cells with a path-length of 10 mm and a width of 2 mm were used. All measurements of absorbance of the ferrous sulphate solution were made at a wave-length of 304 nm and with a spectral bandwidth of 1 nm.

In order to obtain 1 litre dosimeter solution 200 ml distilled water is used mixed together with 22 ml analytic grade H_2SO_4, 1 ml of 1 N NaCl, 1 ml of 0.01 N H_2O_2, a few drops of $KMnO_4$ (until the solution turns to a faint violet colour), and 0.392 g of analytic grade $(NH_4)_2$ $FeSO_4$. Distilled water is then added until 1 litre of the mixture is obtained.

For each new preparation of solution the linearity of absorbance against dose was checked. A linear relationship has always been obtained which indicates that no impurities were present in the solution (COTTENS et coll. 1980). The linearity checks were made in a standardized set-up at a ^{60}Co unit and could therefore also be used as a constancy check for the Fricke system. The standard deviation to these measurements was 0.2 per cent.

Dosimeter cells were made of PMMA (Figure). This material was chosen as it has about the same linear scattering power as water; $T_{PMMA}/T_{water} \approx 1.035$ in the energy range from 0.2 to 50 MeV (T being the symbol for linear scattering power). Perturbation corrections due to in- and out-scattering from the

Table 1

The 'zero-dose' absorbance as a function of storage time for the PMMA cells. The standard deviations are also given

Storage time (hours)	'Zero-dose' absorbance (ODU)
1	0.0001±0.0001
22	0.0003±0.0002

water phantom to the dosimeter solution may therefore be expected to be insignificant. As a comparison $T_{polystyrene}/T_{water} \approx 0.83$ thus giving a larger disturbance due to scattering of the electrons than for PMMA.

The storage effect was investigated for these PMMA cells. Unirradiated solution was stored in the cells during different lengths of time. The 'zero-dose' absorbance was determined as the difference between the readings from solution taken from the dosimeter cells to that of solution from the glass storage bottle (SVENSSON et coll. 1967). The 'zero-dose' absorbance in an experiment with 18 irradiation cells is given in Table 1. The standard deviations are small also for long storage times which makes it possible to make accurate corrections for this effect. An absorbance of 0.0002 ODU corresponds to less than 0.1 per cent of the absorbance ordinarily used for dose measurements. In the absorbed dose measurements the dosimeter solution was irradiated to an absorbed dose of approximately 50 Gy corresponding to an absorbance of approximately 0.2 ODU.

During the experiments the ferrous sulphate dosimeters were rinsed and re-filled immediately before the irradiation and evaluated immediately after. The time between filling and evaluation was in most cases less than two hours.

Determination of absorbed dose

The measured difference in absorbance between the irradiated and unirradiated solution is related to the absorbed dose in the dosimeter solution according to the following equation:

$$\bar{D}_i = \frac{\Delta A_t}{p\, l\, (\varepsilon_m)_t G_{t'}} \qquad (2)$$

where

$\bar{D}_i$ = mean absorbed dose to the dosimeter solution

ΔA_t = increase in absorbance due to irradiation at a temperature t during the spectrophotometric measurement

p = density of dosimeter solution (1.024 g cm^{-3})

l = length of the light path in the photometer cell

$(\varepsilon_m)_t$ = molar extinction coefficient for ferric ions at temperature t

$G_{t'}$ = ferric ion yield at the irradiation temperature t' and at the dose $\bar{D}_i$

All measurements were referred to temperatures t and t' equal to 25°C. A correction for temperatures differing from 25°C was made according to:

$$(\varepsilon_m)_t G_{t'} = (\varepsilon_m)_{25°C} G_{25°C} [1+k_1 (25-t)] [1+k_2 (25-t')]$$

where $k_1 = 0.0069°C^{-1}$ and $k_2 = 0.0012°C^{-1}$ (PETTERSSON & HETTINGER 1967, ELLIS 1974, COTTENS et coll.).

Most of the old investigations of G-values are probably based on measurements with large uncertainties in the determination of ε_m. It was pointed out by EGGERMONT et coll. (1978) that spectrophotometers generally agree much better than the various experimental results of ε_m-values indicate. A systematic error in ε_m will give a corresponding error in the determination of G. This uncertainty has been reduced by SVENSSON & BRAHME by using the various published values of $\varepsilon_m G$ instead of only G. This procedure resulted in a smaller spread in the products among different authors, than the G-value gave. A value of $\varepsilon_m G = 352 \times 10^{-6}$ m^2 kg^{-1} Gy^{-1} was recommended by SVENSSON & BRAHME and was used both for ^{60}Co gamma rays and electrons.

For electron beams the absorbed dose to water, D_w, can be calculated from the mean absorbed dose in the dosimeter solution, $\bar{D}_i$, by the Bragg-Gray relation (ICRU 1972):

$$D_w = \bar{D}_i (s_{w,i})_u \qquad (3)$$

where $(s_{w,i})_u$ is the water to dosimeter solution mass stopping power ratio. For ^{60}Co gamma beams the absorbed dose to water can be calculated by multiplying by the ratio of the mass energy absorption coefficients water to dosimeter solution. A value of $D_w/\bar{D}_i$ equal to 1.003 was used for both electron and ^{60}Co gamma beams.

Table 2

Comparison of absorbed doses determined at different accelerators using plane-parallel ionization chambers and ferrous sulphate dosimetry

Accelerator	$\bar{E}_0$ (MeV)	Depth (mm)	$s_{w,air}$	p_u	$\frac{(D_w)_{ionization\ chamber}}{(D_w)_{FeSO_4}}$
Betatron	27.5	25	0.965	1.000	1.000±0.002
Microtron	19.5	25	0.992	1.000	0.994±0.003
Microtron	18.5	25	0.997	1.000	0.990±0.003
Linear accelerator	18.7	20	0.990	1.000	0.995±0.008
Linear accelerator	9.4	20	1.057	1.000	0.999±0.010
Microtron	8.7	20	1.066	1.000	1.001±0.007
Linear accelerator	6.9	15	1.075	1.000	0.998±0.005
Linear accelerator	5.3	12	1.090	1.000	0.997±0.005
Microtron	4.2	10	1.101	1.000	0.998±0.015
Linear accelerator	3.9	8	1.098	1.000	0.998±0.007
Microtron	2.8	3.7	1.102	1.000	1.001±0.012
^{60}Co	–	50	1.15	0.994	0.992±0.006

Table 3

Comparison of absorbed doses determined using the Baldwin-Farmer ionization chamber and ferrous sulphate dosimetry

Accelerator	$\bar{E}_0$ (MeV)	Depth (mm)	$s_{w,air}$	p_u	$\frac{(D_w)_{Baldwin\text{-}Farmer}}{(D_w)_{FeSO_4}}$
Linear accelerator	18.7	20	0.990	0.990	0.996±0.002
Linear accelerator	9.4	20	1.057	0.965	0.996±0.003
Linear accelerator	6.9	15	1.075	0.960	1.000±0.003
^{60}Co	–	50	1.150	0.965	0.998±0.003

Results

The results of the measurements with the ionization chambers and the ferrous sulphate dosimeter are given in Tables 2 to 4. The last column gives the ratio of the absorbed dose to water, D_w, determined using the ionization chamber and using the ferrous sulphate dosimeter. The ratio for the different electron beams is for most energies slightly less than unity.

The largest deviation (1 to 1.5%) from 1.000 was obtained with the measurement carried out at $\bar{E}_0$=18.5 MeV with the microtron MM22. The reason seems to be that the scattering foils were designed for very large (35 cm × 35 cm) uniform beams. The dose contribution, from roentgen rays generated in the foils, will be approximately 5 per cent at the dose maximum depth (obtained from evaluation of the roentgen ray tail of the depth dose curve). The stopping-power ratios from the NACP are theoretical and refer to a situation without contaminating roentgen rays but include the influence of those photons which are generated in the phantom. A contamination at dose maximum of 5 per cent will mean that $(s_{w,air})_u$ increases by about 0.5 per cent. Furthermore, thick foils give rise to a large number of electrons which are scattered into the collimator system, particularly when fairly small field sizes are used (here 12 cm × 12 cm). Some of these electrons outside the useful beam will be energy degraded and scattered back into the central part of the beam (LAX & BRAHME 1980). The mean energy of the electrons, $\bar{E}_0$, has therefore probably been overestimated and a too low stopping power ratio value is used. An experiment using the same accelerator energy but a scattering foil system constructed for a uniform beam with a diameter of 20 cm lent support to these hypotheses (microtron $\bar{E}_0$=19.5 MeV). The effect can be expected to decrease at large phantom

Table 4

Variation of the ratio $(D_w)_{\text{ionization chamber}}/(D_w)_{FeSO_4}$ with phantom depth for two types of scattering foil systems. The same accelerator energy E_a was used in both cases. The plane-parallel chamber was used for the measurements. The estimated uncertainty in these measurements is ±0.3 per cent

Accelerator	E_a (MeV)	$\bar{E}_0$ (MeV)	Depth (mm)	$s_{w,air}$	$\frac{(D_w)_{\text{ionization chamber}}}{(D_w)_{FeSO_4}}$
Microtron	20.9	19.5	10	0.975	0.994
			15	0.981	0.995
			20	0.986	0.994
			25	0.992	0.994
Microtron	20.9	18.5	10	0.978	0.985
			15	0.985	0.988
			20	0.991	0.989
			25	0.997	0.990

depths. To find if this was the case measurements were made at different phantom depths using the two types of scattering foils (Table 4). As expected the ratio $(D_w)_{\text{ionization chamber}}/(D_w)_{FeSO_4}$ decreases with decreasing phantom depth for the $\bar{E}_0$=18.5 MeV beam, indicating that the mean energy is lower than that determined from the range-energy formula. As the effect depends on the construction of the scattering foil and collimator system it can be expected to be different for different types of accelerators.

Uncertainties. The uncertainties given in Tables 2 and 3 are the standard deviations. The reproducibility in the ferrous sulphate dosimetry system at measurements in ^{60}Co gamma beams is 0.2 per cent. At measurements in electron beams this value is expected to be somewhat higher as the irradiation conditions are more unstable in accelerator beams. The stability of most of the used ionization chambers is better than 0.5 per cent.

The ionization chambers and the ferrous sulphate dosimeters are of different shape and size and will therefore 'see' different areas of the beams. At measurements in beams with poor uniformity this will give a systematic error in the comparison. In the ^{60}Co gamma beams this effect is estimated to be less than 0.3 per cent and in the electron beams even smaller. No corrections for this effect have been carried out here.

Discussion and Conclusion

The ferrous sulphate dosimetry system used in the present investigation was also recently used in an intercomparison of systems operated by national laboratories (ELLIS et coll. 1981). Ferrous sulphate dosimeters were irradiated in a ^{60}Co gamma beam at BIPM in Paris and then returned to the laboratories for evaluation. The ratio of absorbed dose to water now reported and the corresponding estimate given by BIPM was 1.007±0.001. The agreement is therefore acceptable and is adequate for the present use of the dosimeter system.

It has been shown that the absorbed dose determination carried out with the ferrous sulphate dosimeter system and with the ionization chambers applying NACP (1980) and NACP (1981) agree within about one per cent. This is, of course, a very satisfying result as many approximations are made in the ionization chamber dosimetry. Thus, one of the difficulties in the ionization chamber dosimetry is to determine the input parameter for the determination of $(s_{w,air})_u$. It has been shown that for some beams the contamination of low energy electrons is not fully taken into account in the determination of $\bar{E}_0$ resulting in an underestimation of $(s_{w,air})_u$ particularly at small depths. Also for a very accurate dose determination the influence of contaminating roentgen rays must be considered.

SUMMARY

A check of the dosimetry using ionization chambers and applying the procedures described in the Nordic dosimetry protocols (NACP 1980, 1981) was carried out using the ferrous sulphate dosimeter as reference. Measurements have been carried out in electron beams in the energy range 2.8 to 27.5 MeV and in ^{60}Co gamma beams.

Consistent results were obtained with the two systems within about one per cent. Larger differences were only observed in electron beams containing a large proportion of scattered low energy electrons and contaminating roentgen rays which were not corrected for in the ionization chamber method.

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