A standard Fricke dosimeter compared to an ionization chamber used for dosimetric characterization of ^{60}Co photon beam

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Abstract

The main objective of this study was to investigate the Fricke dosimeter water equivalent system for measurement of dosimetric parameters for photon beam. The parameters measured with the Fricke dosimeter were compared to those obtained with an ionization chamber. In this work characteristics for ^{60}Co γ -rays of field sizes ranging from $5 \times 5 \text{ cm}^2$ to $20 \times 20 \text{ cm}^2$ are reported. The measurements were carried out in the secondary standard dosimetry laboratory using a collimated ^{60}Co gamma source therapy unit. The ^{60}Co beam output in terms of absorbed dose to water was obtained as per IAEA TRS 398 recommendations using cylindrical ionization chamber, whose $N_{D,w}$ has been supplied by the IAEA's reference laboratory. Specific quantities measured include: output factors, peak scatter factor, lateral beam profiles and percentage depth dose. The Fricke dosimeters were irradiated in a water phantom using the suitable poly (methyl methacrylate), PMMA stand. Our results demonstrate that Fricke dosimeter and ionization chamber agree with each other.

Key words: Fricke dosimeter; dosimetric parameters; radiotherapy; ^{60}Co ; ionization chamber.

Introduction

Clinical applications of radiation require precise planning and dosimetric measurements. Radiotherapeutic applications of ionizing radiation are expected to deliver to the patient an absorbed dose within 5% of that prescribed by the physician [1]. It is important to previously determine the absorbed dose distribution in the target volume and in adjacent tissues to guarantee the prescribed treatment. For the treatment planning, the dosimetric parameters dependent on the beam energy, target composition and irradiation geometry are necessary to calculate how the absorbed dose will be distributed in the patient target volume (tumor). The parameters percentage depth dose, beam profile and output factor, once obtained, are used in the service routine for patient absorbed dose calculations. The selected dosimetric system must be accurate, reproducible and linear with the absorbed dose.

The literature has presented several types of photon detectors suitable for large and small field size dosimetry, such as ionization chambers, diodes, films, TLD and 3D gel dosimeters [2-5]. In this work we investigated the beam parameters related to photon beam for different field sizes using the chemical Fricke dosimeter and a cylindrical PTW 30013 0.6 cm^3 ionization chamber (IC). We demonstrate that the Fricke dosimeter is adequate for field size photon dosimetry. Its composition contains Fe^{+2} ions that once irradiated are oxidized to Fe^{+3} ions. The concentration of Fe^{+3} , which is generally determined through spectrophotometry, is directly

proportional to the absorbed dose of ionizing radiation. The Fricke dosimeter has been used for many applications such as experimental k_Q photon beam quality correction factors measurements, dosimetry of low energy protons and light ions, intercomparison of absorbed dose to water measurements, output calibration in teletherapy machines with photons and electrons and quality assurance of HDR brachytherapy source [6-11]. This application is based on some good characteristics such as dose rate independence, water-equivalence and energy-independent response for radiotherapy clinical accelerator beams.

We report experimental procedures for correct dosimetry in a water phantom using two different dosimeters and incident γ -rays produced by therapy ^{60}Co unit. Lateral beam profiles, percentage depth dose, output factors, peak scatter factors and output of cobalt source in terms of dose rate to water were measured with each detector for each radiation configuration. The experimental details are given in the following section. For dosimetry procedures, IAEA protocol TRS 398 was employed [2].

Materials and Methods

Preparation of Fricke solution

The Fricke solution was prepared with 10^{-3} mol/L of ferrous sulphate ammonium ($\text{Fe}(\text{NH}_4)_2(\text{SO}_4)_2 \times 6 \text{ H}_2\text{O}$) (analytical reagent grade from Fluka), 10^{-3} mol/L of sodium chloride (NaCl) (analytical reagent grade from Fluka) and 0.4 mol/L of

concentrated sulphuric acid (H_2SO_4) (analytical reagent grade from Merck) and made up to a volumetric flask of 1000 cm^3 with high purity water provided by Arium[®] 611 ultrapure water system manufactured by Sartorius. The system provides water with a typical resistivity of about $18.2\text{ M}\Omega$ at 25°C and total organic carbon less than 4 ppb. The method used for preparation was as described in ASTM (American Society for Testing and Materials) standard E 1026 [12], except that the water-acid mixture is preirradiated to approximately 10 Gy [13,14] before adding the other chemicals, to eliminate non-linearity in the slope at lower doses, resulting from impurities in the acid. The Fricke solutions are prepared in 1 litre batches and stored away from natural and artificial light sources. During manufacturing precautions were made to minimize possible effect of impurities on the Fricke solution. The Fricke solution is transferred from the stock solution to the irradiation ampoules using clean Pasteur pipettes.

The dosimeter ampoules used in this study are glass-walled small bottle-shaped manufactured by FISHER Scientific OSI Company. These have the following dimensions: inner diameter 10.6 mm, height 31 mm (referred to the top surface of the liquid in the ampoule) and Pyrex wall thickness 0.5 mm. Therefore, the volume of the dosimetric solution is 2.7 cm^3 . The ampoule shape was specifically designed so to make it easier to fill and to seal the ampoule without damaging the solution. The ampoule shape also makes it possible to irradiate the dosimeter in vertical beams without any air bubbles in the cylindrical part of the ampoule.

Calibration curve

The calibration of the dosimeters was performed in ^{60}Co γ -rays using an Eldorado therapy 78 unit at a dose rate of about 0.5 Gy min^{-1} to water. The dosimeters were placed in a water phantom $30 \times 30 \times 30\text{ cm}^3$ with their geometrical center positioned at a reference depth of 5 cm, with a source-surface-distance (SSD) of 80 cm and a field size of $10 \times 10\text{ cm}^2$ at the phantom surface. The output dose rate to water was measured previously using a 0.6 cm^3 reference ionization chamber WDIC70 #141 connected to a PTW UNIDOS 10002 electrometer. The reference chamber was calibrated in terms of absorbed dose to water at the International Atomic Energy Agency reference laboratory (Vienna, Austria). The calibration coefficient ($N_{D,w}$) established at the conditions $T = 20^\circ\text{C}$ and $P = 101.325\text{ kPa}$, is thus traceable to the International Bureau of Weights and Measures (Paris, France).

The calibration curve was obtained by irradiating individually filled ampoules at known dose values with a range of doses from 5 to 25 Gy. For each selected dose, four Fricke dosimeters were irradiated and their absorbance values averaged. The absorbance readings were corrected for the influence of both the readout temperature, T_r , and the irradiation temperature, T_i [15, 16]. The reference temperature is 25°C .

Spectrophotometric analysis

The ferric ion concentration in irradiated solution was evaluated using UV-VIS double beam spectrophotometer (Cary 100, Varian, Australia). Absorbance measurements were made at a wavelength of 303 nm, with a spectral bandwidth of 1.5 nm (allowing optimum control over data measurement resolution). The photometer cell had a path length of 10 mm and a width of 4 mm.

Output factor

The output factor (OF) is defined as the ratio between the considered absorbed dose at the center of a selected field size and that from a reference field size $10 \times 10\text{ cm}^2$; both measurements were performed at the depth of maximum dose with all other irradiation conditions identical [2]. Measurements of output factors were carried out by using each dosimeter cited above at SSD of 80 cm and the dosimeters were placed in the central axis at depth d_{max} of 5 mm in the water phantom type Med-Tec $40 \times 40 \times 40\text{ cm}^3$ semi-automatic manufactured by Medical Technology Company. Single Fricke dosimeters were introduced in the water phantom and centered in the field sizes of $5 \times 5\text{ cm}^2$; $7 \times 7\text{ cm}^2$; $8 \times 8\text{ cm}^2$; $10 \times 10\text{ cm}^2$; $12 \times 12\text{ cm}^2$; $15 \times 15\text{ cm}^2$ and $20 \times 20\text{ cm}^2$. During measurements gantry and collimator angles were fixed at zero degree. Each exposure was performed for the same time setting in the cobalt unit for each field size. Four of such Fricke dosimeters were irradiated in the same conditions and their readings values were averaged for each field size. The irradiation conditions with the ionization chamber were the same cited. The field size $10 \times 10\text{ cm}^2$ was used as reference for normalizing the measurements for other fields.

Peak scatter factor

The peak scatter factor, PSF, is defined as the ratio of the dose at d_{max} in a phantom at point P, D_p , to the dose D'_p in air measured with a buildup cap around the point of interest P to provide electronic equilibrium [18]. Peak scatter factors were obtained with each dosimeter for the square field sizes used for OF determinations. Measurements were performed by first placing the dosimeters free-in-air using buildup cap (to provide electronic equilibrium) at the distance of 80.5 cm from the ^{60}Co source. Additional measurements were made with the phantom in place. The phantom type Med-Tec $40 \times 40 \times 40\text{ cm}^3$ semi-automatic is employed as scattering material. The phantom was placed on the irradiation bench of the cobalt unit at the SSD of 80 cm from the beam focus and the centre of the field coincided with the geometric centre of the dosimeters placed at the build-up depth in water of 5 mm. During measurements gantry and collimator angles were fixed at zero degree. Each exposure was carried out for the same time setting in the cobalt unit for each dosimeter configuration and for each field size. Four of such dosimeters were irradiated in the same conditions and their readings values were averaged.

Percentage depth dose

The percent depth dose (PDD) expressed as a percentage, at any depth (d) is the ratio of the dose at that depth to the dose at a depth of maximum dose ($d_{\max}$) [18]. The percentage depth dose measurements were carried for one field size of $10 \times 10 \text{ cm}^2$ in the same phantom used for PSF and OF evaluations, using Fricke dosimeter and 0.6 cm^3 IC. A single Fricke dosimeter and IC were inserted in the water phantom and exposed to the ^{60}Co beam at the SSD of 80 cm. Fricke dosimeters and ionization chamber were irradiated to different constant timings depending upon their respective dose range. Data are collected along the beam axis from the water surface to a depth of 20 cm. For each depth, three Fricke dosimeter and IC exposures were taken. The readings are then normalized to the maximum dose and expressed as percentage following the relation:

$$PDD = \frac{D_d}{D_{d_{\max}}} \times 100 \quad \text{Eq. 1}$$

Beam profiles

The beam profiles were obtained with each dosimeter for the field sizes of $5 \times 5 \text{ cm}^2$ and $10 \times 10 \text{ cm}^2$. Irradiations were made in the same phantom used for PSF and PDD measurements, at 5 cm depth in water with the SSD of 80 cm. The Fricke dosimeters were expanded laterally (in amounts of 9 and 16, to provide the expected field size lengths) on the PMMA plate with dimensions $10 \text{ cm} \times 25 \text{ cm}$ and 1 cm thick. Then, the plate was introduced in the phantom and positioned at d_{ref} . All dosimeters were exposed to an irradiation time yielding a dose of 5 Gy at 5 cm depth. Three exposures were taken for each dosimeter conformation to derive an average value of absorbed dose at the reference depth as a function of lateral distance from the beam axis for each field size.

The ionization chamber has been moved laterally in steps of 1 cm along the x-axis between each irradiation. The exposure time was 30s. Three readings were done for each point selected to obtain an average value. The measured profile values were then normalized to the maximum value, at the field center.

Output cobalt source

Output of the ^{60}Co source in terms of dose rate to water was carried out by using each dosimeter cited above. The dosimeters were placed in the IAEA standard water phantom with their geometrical center positioned at a reference depth of 5 cm, with an SSD of 80 cm and a field size of $10 \times 10 \text{ cm}^2$ at the phantom surface. Single Fricke dosimeters were introduced in the water phantom and centered in the field size. During measurements gantry and collimator angles were fixed at zero degree. The exposure time was chosen that would deliver a total dose of 25 Gy at 5 cm in water. Four Fricke dosimeters were irradiated and their absorbance values averaged. The absorbance readings were corrected for the influence of both the readout temperature, T_R , and the irradiation temperature, T_i .

As it is known, the absorbed dose to water as determined by Fricke dosimeter, $D_{w,F}$, can be expressed:

$$D_{w,F} = \frac{\Delta A}{\epsilon G(\text{Fe}^{3+}) \rho l} f P_{\text{wall}} \quad \text{Eq. 2}$$

where ΔA is the difference in absorbance between the irradiated and unirradiated Fricke solution at 303 nm, ϵ is the molar extinction coefficient of Fe^{3+} at 303 nm measured at our laboratory and found to be $220.1 \pm 0.3 \text{ mol m}^{-2}$, ρ is the density of the Fricke solution (1.024 g/cm^3), l is the length of the light path of the photometer cell (0.01m), f is the absorbed dose conversion factor which converts the dose to Fricke solution in a wall-less vessel to the dose to water (1.003 is the mean value taken from the Ref. [17]), and P_{wall} (0.9978) is a perturbation correction factor that accounts for the effect of the wall material of the Fricke vial. In this work the P_{wall} value was determined using the data obtained from Monte Carlo calculations for P_{wall} given in Ref. [17] for NPL vials, because these vials are similar to those used in our laboratory. To facilitate their use these data have been fitted to a simple linear expression in terms of the tissue-phantom ratio, TPR_{10}^{20} .

$$P_{\text{wall}} = 1.02076 - 0.04002(TPR_{10}^{20}) \quad \text{Eq. 3}$$

The value of TPR_{10}^{20} for ^{60}Co radiation quality investigated in this work was measured and was found to be 0.573. Substitution of this value into **equation 3** yields P_{wall} value of 0.9978.

The ionisation chamber measurements were performed in the geometry described above. Ionization readings were collected after an exposure time of 30 s; ten readings were made and averaged.

Results and discussion

Calibration curve

In **figure 1** the dosimeter absorbance versus absorbed dose to water is shown in the interval of 5 Gy – 25 Gy for ^{60}Co γ -rays. This dose response curve is linear with a differential absorbance sensitivity $\Delta A/D_w$ of about 0.0036 Gy^{-1} , where D_w is the value of absorbed dose in water as measured by the standard ionization chamber, and ΔA is the difference in absorbance between the irradiated and unirradiated Fricke solution. The absorbance readings were corrected for the influence of both the readout temperature, T_r , and the irradiation temperature, T_i . The linear interval investigated is consistent with the results reported elsewhere [14] and is adequate for radiotherapy purposes.

From the result above, by equating $D_{w,F}$ in **equation 2** to the absorbed dose to water measured by the reference ionization chamber, D_w , we calculate the radiation yield of Fe^{3+} , $G(\text{Fe}^{3+})$, in **equation 2**. We measured $G(\text{Fe}^{3+})$ to be $1.598 (\pm 0.012) \mu\text{mol j}^{-1}$. The G value obtained is comparable within experimental error with the published value in reference [14].

The basic data set that follows is relative to each dosimeter response at a given position and depth, and did not use the calibration curve.

Figure 1. Fricke dosimeter calibration curve for ^{60}Co energy photons, $10 \times 10 \text{ cm}^2$, 80 m SSD at 5 cm depth in water. An error bar shows the standard deviation (1σ) of each set of measurements.

Figure 2. Output factors versus square field size for ^{60}Co at 80 cm SSD and at reference depth. The relative standard deviations of the mean is about 0.5% for Fricke dosimeter and 0.02% for 0.6 cm^3 IC.

Figure 3. The effect of field size on the peak scatter factors from the water phantom for ^{60}Co . The relative standard deviation of the mean is about 0.6% for Fricke dosimeter and 0.02% for 0.6 cm^3 IC.

Output factor

Figure 2 shows the relative output factors for square fields measured with Fricke dosimeter and ionization chamber. Comparing the illustrations in the above figure; the values of OF determined with the aid of the Fricke dosimeter agreed to within 0.5% with values obtained from ionization chamber measurements.

Peak scatter factor

Peak scatter factors carried out with the Fricke dosimeter and ionization chamber for square field sizes using a water phantom as scattering material are shown in figure 3. In this figure, besides the measured PSF graphs, the graphs of published data of PSF in the British Journal of Radiology (BJR) supplement 17 [19] and in the BJR supplement 25 [20] were included. A good agreement between the PSF measured by both systems was found. Comparing the graphs in the above figure, we have got a deviation of maximum less than 1%

Figure 4: PDD versus depth in water (cm) for square field size $10 \times 10 \text{ cm}^2$ at ^{60}Co γ ray, 80 cm SSD.

between our measured values and those given in the BJR supplement 17; the data published in the BJR supplement 25 were about 2% higher than our results, possibly an attribute that owes to the method used for determination of the PSF. We also note that when the field size increases the PSF increases slightly. This could be attributed to the increase in a number of backscattered particles from the phantom as the field size increased [21].

Percentage depth dose

Figure 4 presents the percentage depth dose measurements (PDD) for $10 \times 10 \text{ cm}^2$ field size performed with Fricke dosimeter and ionization chamber and a reported tabulated values of the PDD for ^{60}Co gamma rays beam in the BJR supplement 25 [22]. Evidently, both dosimeters agree between each other. Comparative plots shows well matching between our measured PDD values and those published in the BJR supplement 25.

Beam profiles

The ^{60}Co photon beam profiles are illustrated in **figure 5** for the field sizes performed with Fricke dosimeter and ionization chamber. According to the previously published protocols [1,23], to judge the acceptability of each data set for each field and dosimeter, the field profile evaluation can be done considering the homogeneity, symmetry and penumbra characteristics.

The accepted tolerance for homogeneity is $\leq 2\%$. In our case differences of less than 1.02% were inferred for both field sizes and dosimeters.

The accepted tolerance for symmetry is $\leq 2\%$. In our measurements deviations of less than 1.30 % were observed for both field sizes and dosimeters.

The accepted tolerance for penumbra is ≤ 2 mm. The Fricke dosimeter and ionization chamber agree within 1 mm in profile position.

Output cobalt source

The ionization readings were corrected for temperature and pressure leading to the mean reading which was used to estimate the absorbed dose to water according to the TRS 398 formalism. The absorbed dose to water derived from ionizations measurements was $0.2576 (\pm 0.0001)$ Gy yielding a dose rate to water of $0.5152 (\pm 0.0001)$ Gy min^{-1} .

The measured absorbance of the Fricke solution ΔA obtained was 0.0899. Therefore, the estimated absorbed dose to water in Gy was evaluated using the **equation 2** assuming all parameters cited above. The calculated absorbed dose to water was $24.98 (\pm 0.001)$ Gy and the associated dose rate to water was $0.499 (\pm 0.001)$ Gy min^{-1} . The uncertainties quoted here are primarily statistical and indicate the precision obtained with each dosimeter.

The values of absorbed dose obtained from Fricke dosimeter measurements agreed to within 0.1% with the values obtained from ionization measurements.

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Figure 5. Field size profiles as obtained with the aid of Fricke dosimeter and an ionization chamber with 80 cm SSD for ^{60}Co energy photons at 5 cm depth in water. The relative standard deviation of the mean is about 0.5% for Fricke dosimeter and 0.02% for 0.6 cm³ IC.

Conclusion

From our measurements we conclude that our Fricke dosimeter gives results that are consistent with the expectations of ionization chamber. Considering the dosimetric parameters results obtained, one can treat the Fricke dosimeter as an adequate dosimeter for conventional field sizes measurements. In this way we can conclude that this dosimeter usually used for reference dosimetry can be used for general radiotherapy control through the dosimetric parameters measurements. The results of this study encourage us to investigate in the future the Fricke dosimeter for dosimetry of small fields. Because in this case, a dosimeter with high resolution is required.

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