Radiochromic Gel Dosimeter (FXG) Chemical Yield Determination for Dose Measurements Standardization

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Abstract. Different gel dosimetry techniques have been proposed as methods for three dimensional dose distribution measurements. Gel dosimeters were proposed for radiotherapy dosimetry at which the calibration of any dose-measuring technique is the main requirement for its proper practical application. The standardisation of the technique requires the establishment of a method for the calibration of each type of these gel materials. The aim of this study is to determine the chemical yield for the radiochromic “Ferrous-sulphate and Xelenol-orange Gelatin” (FXG) gel. Using standard absorbed dose to water protocol, the radiation field is calibrated first; then a standard Fricke solution dosimeter is calibrated. The obtained chemical yield for Fricke is \( G(\text{Fe}^{3+}) = 1.68 \times 10^{-6} \) [mol. J\(^{-1}\)]. Finally, FXG dosimeter was calibrated against the standard Fricke solution before calculating the system chemical yield and comparing its value with Fricke system. The results show that \( G(\text{FXG}) = 6093.1 \) [m\(^2\). J\(^{-1}\)] = 19.5\( \times \)\( G(\text{Fricke}) \). Compared with the Fricke system, the FXG dosimeter has much higher sensitivity. Additionally, the overall accuracy and reproducibility of the gel detector was also comparable to those reported for Fricke solution. However, the FXG dosimeter properties could be improved further through the establishment of a defined manufacturing procedures and calibration method; as well as precise selection of sensitive materials and radiation effects evaluation techniques.

1. Introduction

A dosimetric system that can precisely measure radiation dose variations in three dimensions with high spatial resolution is highly demanded for various applications. An obvious example is radiotherapy dosimetry, where assessing and measuring the absorbed dose accurately is essential to achieve a successful treatment. In practice, due to the complexity of the treatment procedures and the use of sophisticated irradiation facilities, most of the required information is obtained using complex computational methods. Such techniques are usually time consuming and need extremely accurate calibration. The theoretical calculations and computer simulations are also unlikely to have absolute accuracy, and they are susceptible to human errors and unexpected problems. Therefore, in all 3-D dosimetry investigations the prime objective is to find practical systems that are able to measure the dose distribution in three dimensions with sub-millimetre resolution in a non-invasive, non-destructive and accurate way. Such measurements would be valuable on their own, and they might also be used to check whether the expected dose distributions for computationally controlled photon beams are

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achieved in practically. One of the main aims of treatment planning in radiotherapy is that the absorbed dose distribution inside the target volume must be within closely specified limits in order to ensure complete destruction of malignant cells. It is also important to achieve very steep dose gradients are achieved at the boundaries of the irradiated region in order to protect all healthy surrounding tissues. Accurate absorbed dose measurement is an essential factor to attain these objectives. The previously presented dosimetry approach aims at obtaining a complete 3-D dose distribution within materials that are tissue-equivalent, sensitive to ionizing radiation, and they can form part of a phantom to imitate the tumor volume in size, shape and/or composition. The method utilizes high-resolution tomographic imaging methods capable of mapping complex dose distributions such as those applied in conformal radiotherapy, using suitable materials in which radiation effects can be visualised and quantitatively measured.

In summary, radiation dose measurement is an integral part of all radiation treatment procedures. An accurate dosimetry protocol helps not only ensure a high probability of short term success in radiotherapy only, but also helps to improve the health outcome for people undergoing this kind of treatment. As a matter of fact, the objective of radiation therapy is always to deliver a sufficient dose to the tumor while minimizing both the short and long-term risks. Carefully planned radiotherapy procedures must always consider the twin objectives of delivering adequate radiation energy to the targeted tumor, and at the same time minimizing the exposure of the surrounding normal tissues.

2. Experimental Methods

Absorbed dose measurements following standard protocol [1] is performed in order to define the radiation field. A standard ionization chamber is always mounted at the center of the beam to monitor all delivered doses. Fricke dosimeter was prepared and used according to standard procedure [2]. Then FXG is prepared according to a defined method described in [3] and calibrated against the Fricke system.

2.1. Irradiation

A Theratron-Elite-80 $^{60}$Co radiotherapy machine with 10×10 cm$^2$ collimated square field at source to surface distance (SSD) of 100 cm is used for irradiation. The dose rate of 2.1 Gy/min at the gel samples position 5 cm depth in water phantom was applied to obtain a dose response to $\gamma$-rays for both Fricke and FXG dosimeter. Samples were used in each irradiation and the delivered doses are increased up to 10 Gy, figure 1. Irradiation is usually made within 12 hours after the preparation of the sensitive materials, and the optical absorption measurements are recorded 30 minutes after irradiation. Standard ion chamber (0.6 cc) is mounted at the center of the beam to give immediate dose readings.
2.2. Optical spectroscopic measurements

A powerful double-beam UV-visible spectrophotometer SPECORD 210 (analyticjena AG, Konard-Zuse-Str., 1-07745, Jena, Germany) is used in order to perform the optical density measurements (OD), in 1 cm path length in the gel samples. Samples placed in cuvette containers are evaluated before and after irradiation. Wavelengths scan mode is used first to obtain full absorption spectrum in the visible region. Then, a suitable wavelength for FXG dosimeter is selected to make quantitative measurements. The selected wavelength $\lambda=565$ nm corresponds to the maximum changes induced by ionizing radiation interactions at 10 Gy absorbed dose level.

3. Results and Discussion

A dosimeter is said to be absolute if it can be used to measure the absorbed dose deposited in it without requiring calibration in a known radiation field. The Fricke solution is perceived as being capable of absolute dose measurements in some cases when strict requirements are met. It is usually employed as a relative dosimeter because its response depends upon the conversion coefficient called the chemical yield $G(\text{Fe}^{3+})$ that has to be accurately determined in national standards laboratories. The established chemical yield value for the conventional standard Fricke solution does increase by adding organic substances to the system. Getting higher chemical yield makes the system standardization hard to achieve. Gel dosimeters usually contain additional organic materials to initiate a chain reaction that leads to a higher chemical yield [4]. Similarly, FXG contains large quantities of organic materials, mainly gelatin plus the metal ion indicator which complex chain reaction that lead to higher chemical yield.

\[
A-A_0 (\text{FXG}) = 0.0694 D + 0.015 \\
R^2 = 0.9948
\]

\[
A-A_0 (\text{Fricke}) = 0.0032 D - 0.0003 \\
R^2 = 0.9981
\]

**Figure 2:** A comparison between the dose response of Fricke and FXG dosimeters.

Therefore, we propose a procedure for the calibration of FXG gel dosimeter against the standard Fricke system since both systems are similar in terms of the initial chemical reaction as a result for the radiation interactions. FXG response compared to that of the Fricke dosimeter in the dose range of 0-30 Gy is plotted in figure 2.

Chemical yield $G$ is the basic quantity that can be used to calibrate FXG against the Fricke solution. Accurate determination of $G$ is difficult; however, it is possible to take the product $\varepsilon G$ instead of the individual values for molar linear absorption coefficient and the chemical yield, $\varepsilon$ and $G$, as it was recommended for the standard Fricke dosimeter [5]. Doing so help avoiding large systematic errors found in the measurements of $\varepsilon$.
Where, $\Delta A$ is the measured changes in the optical absorbance, $D$ the given dose $\rho$ is the sample's density and $d$ is the optical path length which is normally 1 cm. The evaluation of the $\varepsilon G$ give a good estimate of the relative sensitivity of the radiochromic FXG gel dosimeter, which can be used as a calibration procedure if it is compared with the standard Fricke system, table 1.

**Table 1:** Fricke and FXG dosimeters are compared and the FXG relative sensitivity was calculated.

| Dosimeter Property | Fricke Dosimeter | FXG dosimeter |
|--------------------|------------------|---------------|
| $\Delta A$         | 0.0032           | 0.0694        |
| $\rho$             | $1.024 \times 10^{-3}$ kg.m$^{-3}$ | $1.139 \times 10^{-3}$ kg.m$^{-3}$ |
| $\varepsilon G$    | 312.5 m$^2$.J$^{-1}$ | 6093.1 m$^2$.J$^{-1}$ |
| Relative Sensitivity | 1               | 19.5          |

The system stability can be divided into pre-irradiation stability and post-irradiation stability. First of all, the dosimeter properties should be stable before being put to use. Storage conditions including temperature, light, humidity, etc., as well as the purity of the system materials may cause some changes with time and may affect the dosimeter reading in the absence of radiation. Ferrous ions in the FXG oxidize slowly and as a chemical system suffer the same sort of pre-irradiation changes as the Fricke system. This self-oxidation is reported to be proportional to the square of the ferrous ion concentration [6]. Self-oxidation process cannot be avoided because dissolved oxygen exists in the system and is also needed for the system to function properly. However, the effect can be minimized by cutting in half the amount of ferrous ions in the system, which reduces the natural oxidation process by two folds. In all cases, however, leaving one sample from the same preparation batch un-irradiated, as a control, provides a correction for this effect and, hence, dose measurements should always be normalized by the control reading.

The dosimeter reading stability, after it has been exposed to radiation, is an important quality in any dosimetry system and especially the one that provide integrated dose measurements. Most systems show some sort of unavoidable changes. It is advantageous to make these changes as small and as reproducible as possible, therefore the post irradiation effects can be estimated and suitable corrections are applied during the standardization of the techniques. It was found that keeping the irradiated samples in a cool dark place minimizes these post irradiation effects.

The concept of reproducibility describes the effects of system properties fluctuations, the ambient conditions, and the nature of the measured radiation fields. The reproducibility can be expressed by calculating the random errors and can be estimated from the data obtained in repeated measurements. Usually, these random changes are expressed in terms of standard deviation. The FXG system consists of a number of chemicals each having its own effect on the system performance, plus the effects of environmental conditions during the preparation, irradiation, evaluation and storage. All mentioned causes contribute to the noticed variations in the system response between different dosimeter batches. However, for a set of samples prepared at the same time from the same materials stock and under similar ambient conditions, the system gives adequate reproducibility and satisfactory results. The main sources of errors can be traced to firstly, errors occurring during the preparation, and to the type of used chemicals. Secondly some errors might originate during the irradiation process and dose measurements calibration. Thirdly, standard errors originate from various equipment and tools employed or the methodology being followed; human errors are also expected at the stage of data acquisition and analysis. Finally, the dose calculation, using FXG depends on the value of the chemical yield factor which is not precisely defined and therefore leads to unavoidable calibration errors. Experimentally, the errors of a particular preparation are estimated by measuring a set of un-irradiated samples together with another set, from the same preparation, irradiated to 10 grays in a $^{60}$Co gamma radiation field.
**Table 2:** FXG precision in particular set of samples taken from the same batch.

| Description                           | A cm$^{-1}$ at 565 nm | $\sigma$ % |
|---------------------------------------|------------------------|------------|
| Un-irradiated samples                 | 0.157                  | 3.181      |
| Un-irradiated samples measured after 24 hours delay | 0.160                  | 3.125      |
| Sample irradiated to 10 Gy            | 0.372                  | 3.433      |

Table 2, shows the mean values and the percentage standard deviation in the reading of ten samples from the same batch. Here the readings are expressed in terms of the optical density at the measuring wavelength 565 nm, for un-irradiated FXG samples and another set of FXG samples exposed to 10 Gy.

**4. Conclusions**

It is essential to calibrate the gel system before using it in practice for radiotherapy dosimetry. The method described above offers the possibility to calibrate the gel dosimeter against standard system of similar type like the standard Fricke solution. Using standard procedure to prepare and use the gel detector will minimize errors and provide higher accuracy and reproducibility for the system.

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