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Improved Dosimetry in Radiotherapy with Gold-Coated Fiber Optics

Mohammed S Mohammed[1]* , Zeinab A Said[2,3], Asmaa M S Mohammed[3,4]

[1]Department of Cancer Biology, National Cancer Institute, Cairo University, Cairo, Egypt

[2]Department of Physics, Faculty of Engineering and Physical Studies, University of Surrey, Guildford, Surrey,UK

[3]Department of Biophysics, Faculty of Science, University of Cairo, Cairo, Egypt

[4]Medical Physics Unit, Department of Radiotherapy, National Cancer Institute, University of Cairo, Cairo, Egypt

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***Corresponding author:** Mohammed S Mohammed, PhD, Department of Cancer Biology, National Cancer Institute, Cairo University, Cairo, Egypt, ORCID ID: 0000-0001-6003-8586, E mails: m_famy@hotmail.com and m_famy@cu.edu.eg

ABSTRACT

Background: Patients receiving radiotherapy, a clinical treatment process in which radiation is used for the treatment of various types of cancer, utilize a variety of radiation sources with unique characteristics and procedures. In vivo dose measurements can help identify systematic and random errors in delivery of the treatment and therefore play an important role in quality assurance. Recently, the photon response of optical fibers has been investigated by many research groups. The small diameters of optical fibers increase the possibility of producing a dosimeter with high spatial resolution, important in the sense that an accurate value for the absorbed dose in the surrounding tissue of the dosimeter can be more accurately reported. Another important advantage of optical fibers as radiation dosimeters is that, unlike conventional TLDs, optical fibers are impervious to water. The aim of this study is to verify the dosimetric use of fiber optics in interface dosimetry and to investigate a novel enhanced dose technique using different gold thicknesses as a coating for fiber optics.

Methods: To achieve this goal, commercially available Ge-doped SiO_2 optical fibers (Cor Active, Canada) with a core diameter of 50.9 ± 4.1 μm were irradiated using a 250 kVp superficial X-ray machine and a dose of 3 Gy. Before irradiation, fiber optics were prepared and the following steps, preheat annealing and reading, were performed.

Results: The results show enhancement with increasing gold (Au) thickness, with the highest percentage dose enhancement of approximately 160% obtained at 80 nm. A slight deviation from the enhancement was obtained at 20 nm, the first thickness of gold. Encouraging results from such studies have paved the way for the development of optical fiber radiation dosimeters specifically tailored to the task of dosimetry in radiotherapy.

Conclusion: An optical fiber dosimeter can be placed within the tissue of interest, which is applicable due to its flexibility.

Keywords: Fiber optics, Gold coating, In vivo dosimetry, Radiotherapy

1. Introduction

As a consequence of using radiotherapy in approximately 40-60% of all cancer cases[1], the accuracy of this modality is being continuously improved and monitored. Wherefore, all disciplines of radiotherapy are striving to offer accurate medical care for each patient. To achieve this goal, the main action will be to improve dosimetric techniques and protocols[2]. As a procedural application of the international recommendations[3], in vivo measurements of dose can help identify systematic and random errors in the delivery of radiation treatment and therefore play an important role in quality assurance of treatment[4]. Hence, clinical scientists have proven that a large variety of radiation dosimetry methods aim to quantify the amount of energy that is deposited upon interaction with ionizing radiation[2]. Among these varieties, one of the most common dosimeters worldwide is thermoluminescent (TL), which is a characteristic of many crystalline materials. When such a crystal is exposed to radiation, a very minute fraction of the absorbed energy is stored in the crystal lattice in electron traps formed from dopants/ impurities. If the material is subsequently heated, some of this energy can be recovered as visible light[5], the intensity of which is directly proportional to the original radiation intensity. For many organizations, thermoluminescence dosimetry (TLD), the most widely used cost-effective dosimetric technique, has been chosen for routine occupational radiation exposure monitoring. While the phenomenon of TL can be observed in many materials, relatively few of these materials have been found to have good dosimetric characteristics[6].

Basically, an optical fiber is a transparent material used to efficiently transmit light and plays an important role in daily life. Its technology is widely used in diverse civilian applications, including communication networks and sensors for the detection of corrosion in the aircraft industry[7]. Moreover, different biomedical applications have been developed, ranging from laser delivery systems, to disposable blood gas sensors, to intra-aortic probes[8]. The importance of fiber optics for radiation dosimetry has been increasingly recognized over the past decade for dosimetric characterization. The British Research Group has investigated Ge-doped optical fibers as radiation dosimeters, which provide good reproducibility and a linear response to doses over a wide dose range, with a low limit of detectable dose[9]. Clinical scientists have investigated the TL performance of irradiated fibers, which have shown considerable potential for dosimetric applications in radiotherapy, due to their small size, high flexibility, ease of handling and low cost in addition to their good dose response and low fading[9,10]. The TL characteristic of SiO_2 is based on trapping processes, most easily described for crystalline media and is dependent on the presence of structural defects in the material due to the presence of the doped material[10]. The TL response of doped SiO_2 optical fibers has now been investigated using a wide range of radiation types and energies[9,11-14] to investigate photon response. Other groups have used electron beam irradiation[11] and proton beam irradiation[15]. Recently, in the UK, in vivo dosimetry (IVD) has been shown to be an essential procedure for safer radiotherapy[16]. Hence, studies at the Egyptian National Cancer Institute, compared different dosimetric tools in the modality of spatially fractionated radiotherapy (SFRT) and recommended the establishment of a new dosimetric approach that can detect a small field of 1 cm with high reproducibility and accuracy[17,18]. Therefore, this study used commercial telecommunication fiber optics coated with gold to enhance the dosimetric behavior of patients[18], especially for small field size radiotherapy[17].

2. Materials and Methods

Commercial Ge-doped SiO_2 optical fibers; Cat (MM-50/125): optical properties: losses @850 nm ≤10 dB/ km @ 900 nm & losses @1300 nm ≤10 dB/km, {typical core diameter 50 µm// cladding diameter 125.0 ±0.1 µm that provided by Corrective, Canada, were used in this study. To investigate the enhancement achieved by the high atomic number of the gold coating for the dose measured by the fiber optics, the following practical methodology was used:

2.1. Preparation of fiber optics

A. **Remove of the acrylate coating:** The outer acrylate coating is carefully removed using a fiber mechanical stripper. The remaining fiber is then cleaned using a pad of cotton moistened with a small amount of methanol to remove any residual polymer coating[12]. **(Figure 1)**

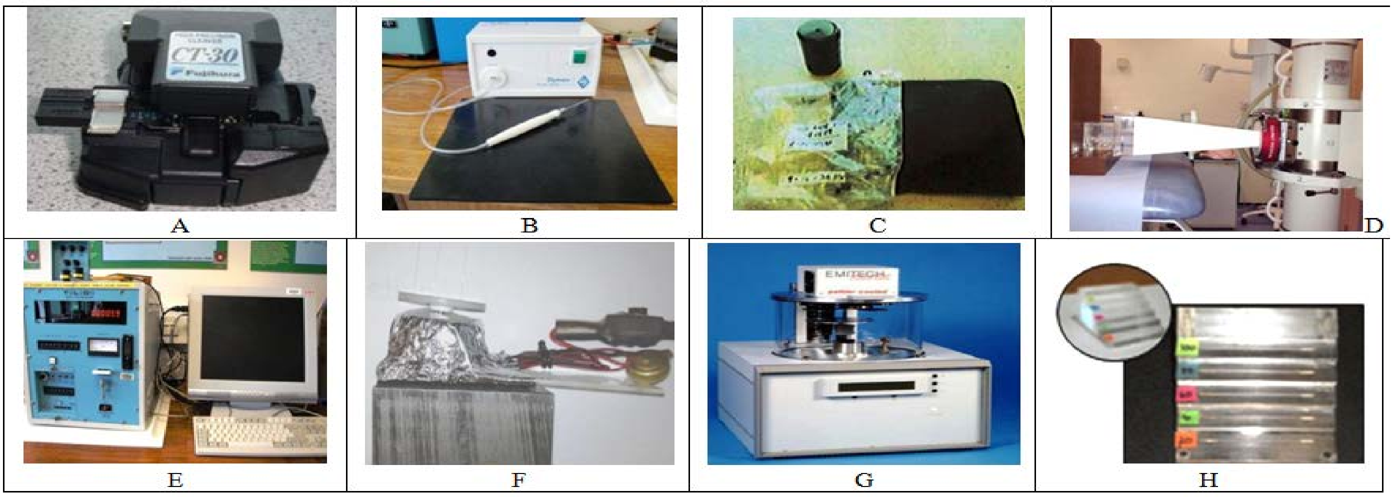

Figure 1: Shows the tools and instruments used to prepare fiber optics as a dosimeter;

A: CT 30 cleaver (Fujikura, Japan);

B: vacuum tweezer;

C: storage of the fiber optics in gelatin capsules retained in an opaque cover;

D: irradiation room, showing the setup of irradiation;

E: TOLEDO TLD readout machine;

F: solar fan motor and fiber optic;

G: coating instrument;

H: the phantom and its different steps.

B. Cutting the fibers: small pieces of fiber optics were cut and divided into two groups: one group was coated with a gold layer and the other was the uncoated control group. A total of 140 pieces of fiber optic tissue, each with a length of 1 ± 0.1 cm and another group of fibers of the same number, cut into lengths of 0.5 ± 0.1 cm, were prepared by a CT 30 cleaver (Fujikura, Japan), the results of which are presented in Figure 1A. To reduce the uncertainty in TL yield, the gross TL yield was normalized to the unit mass of each irradiated fiber and an electronic balance was used to ensure that the mean mass of the fiber and standard deviation were 4.5 ± 0.02 mg.

C. Storage and handling of the fiber pieces: Vacuum tweezers, which are shown in Figure 1B, were used to handle the fiber optic pieces[19]. To ensure unimpeded reception of luminescence yield by the photomultiplier tube arrangement within the TLD reader, it is essential that TLD materials do not become contaminated, particularly with grease[19]. Moreover, the TL sensitivity, stability, reusability, precision and minimum detectable dose for optical fibers may be affected by other physical and environmental factors[20]. Then, the optical fibers were placed into gelatin capsules to avoid exposure to elevated humidity and corrosive agents because these environmental parameters have been shown to reduce sensitivity by enhancing fading[21]. In addition, the capsule temperature decreases when exposed to high ambient light levels, the optical fibers were kept in a darkened environment prior to being irradiated or read out[22]. Figure (1C) shows the fiber optic encapsulation and storage methods.

D. Annealing procedures: The fibers were first annealed in a furnace (Carbolite, UK) before any irradiation or subsequent TL measurements were taken. For annealing purposes, the optical fibers were placed in a ceramic boat and covered with aluminum foil before being placed in the middle of the furnace. The temperature in the furnace was gradually increased from room temperature to 420°C, after which the mixture remained at that temperature for a period of 1 hour. To minimize thermal stress, the samples were then left in the oven for 18 hours to finally equilibrate at room temperature. This annealing step of TL material is carried out when the fibers are to be used for the first time or to be reused for three reasons: to find a good combination of annealing temperature and time for erasing any effect of previous irradiation, to produce the lowest intrinsic background and the highest sensitivity and to obtain reproducibility for both TL and background signals[21].

E. Screening process: Prior to the use of TL dosimeters in clinical practice, they should be screened by irradiating them with a known dose from a calibrated radiation source, which is related to the conditions for which the dosimeters will be used[22]. This process, which is shown in Figure 1D, enables the selection of samples that show good beam uniformity. Figure (1E) shows the instrument used to measure and choose a suitable fiber optic yield. Any TL sample outside the specified tolerance limits was rejected (see Figure 2 A). According to ICRU specifications, this was chosen to be within a limit of ±5% of the group mean[3], which is illustrated in Figure 2B, **(Figure 2)**.

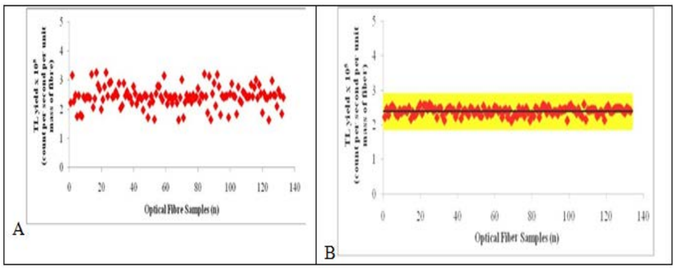

Figure 2: A: The TL yield of the optical fibers for each individual (the screening curve).

B: The TL yield variation for the remaining optical fibers after the selection process.

F. The Glow Curve: The common method of presenting TL data is to plot light intensity against temperature or time, which is called the glow curve (represented in Figure 3). With increasing temperature, the light intensity increases as more electrons are released from the trap and allowed to excite. A decrease in light intensity occurs as the trap is gradually depleted. The number of peaks in a glow curve corresponds to the number of different types of traps existing in the TL material. The temperature at which the maximum of each peak occurs is correlated with its energy depth, E. The area under a glow curve is related to the number of electrons trapped and, in turn, corresponds to the quantity of absorbed radiation[23]. One of the important experimental problems in TL is the presence of several overlapping peaks within the TL glow curve. Very few experimental methods exist that allow decomposition of the TL glow curve into its individual components[24].

G. Gold coating process: First, 1 cm long pieces of fiber optics were prepared for coating by adhering them to small discs of hard card paper. These discs were centrally located on a miniature low inertia solar fan motor, the latter being protected by an aluminum foil cover that also covered the battery. Figure (1F) shows the low inertia solar fan motor and fiber optic samples attached to the centrally located card paper disc.

The five discs with ten fibers per disc were coated with gold in five steps as follows:

- 20 nm thickness - 40 nm thickness - 60 nm thickness - 80 nm thickness - 100 nm thickness. Figure (1G) shows the coating instrument used (K675X Turbo Large Chromium Coater 8; Quorum Technologies Ltd., Kent, UK). After the coating, the optical fibers were ready for irradiation, together with their corresponding uncoated (control) fibers.

H. Gold etching: The TL yield from the fiber optics is strongly affected by the presence of gold during reading, so the gold should be removed. The gold-etching methodology uses aqua regia;

A mixture of concentrated nitric acid and concentrated hydrochloric acid at a ratio of 1:3 was used for gold removal from the fiber optics[25].

2. X-Ray Machines Used in the Experiment

An X-ray machine with potentials ranging from 150 to 500 kV was used. The operating voltage ranged between 200 and 300 kV and the current was between 10 and 20 mA. Filters of different designs are used to achieve half-value layers between 1 and 4mm Cu.

2.1. Irradiation of the fibers: The fibers were put in gelatin capsules and irradiated at Royal Surrey County Hospital, Guildford, UK, using an orthovoltage X-ray unit (GULMAY MEDICAL, Surrey UK), which has a 1 mm lead window. The half-value layer HVL is 2.7 mm Cu, the FSD is 50 cm, the added filtration in mm is 1.5 mm Al + 0.25 mm Cu + 0.5 mm Sn, the tube current is 12 mA and the tube potential is 250 kVp. The optical fibers were exposed to a 3 Gy single dose.

2.2. Reading the fibers for screening: The two requirements for determining the dose given to the fiber optics are a reliable form of heating and a method of measuring the light output[19]. To maintain control of thermal fading, the readout was performed after a set period post irradiation of 12 hours. The TLD reader used was a TOLEDO system (Pitman Instruments, Weybridge, UK), which is presented in Figure 1E.

The readout was carried out in the presence of nitrogen gas to prevent the influence of triboluminescence. In addition, this reduces the amount of oxidation that would otherwise occur on the surface of the dosimeter. Triboluminescence is caused by the mechanical disturbance of the surface of the fiber when the fiber is cut into small pieces[20].

The parameters that provided an optimal glow curve and were used during the readout process were as follows: preheating temperature of 160°C for 10 seconds and readout temperature of 300°C for 25 seconds with a ramp rate of 25°C/sec. An annealing temperature of 300°C for 10 seconds was subsequently used to eliminate any residual signal; its reproducibility was (±1.5) and a low residual signal was obtained for a readout temperature of 300°C and negligible fading. After reading and performing the statistical analysis for the screening process, the steps for coating and subsequent irradiation were carried out.

2.3. The irradiation setup of the fiber optics inserted in the phantom simulated the RT dosimeter:

The optical fibers were distributed in the phantom in steps according to their gold coating thickness. The phantom, a model for the synovial membrane, is formed of a Perspex cube with a length of 7 cm[26]. The phantom was designed at the University of Surrey. Figure (1 H) illustrates the shape of this phantom and its different steps. The irradiation setup was the same as that for the screening process, with the same monitoring units, time and dose rate.

3. Results and Discussion

3.1. Screening optical fibers

The Ge dopant distribution in the longitudinal direction of fiber optics is heterogeneous and provides for TL radiation dosimetry applications; thus, the TL yield will be affected[27].

The selection of fiber dosimeters with uniform sensitivity is important for allowing further investigation of the enhancement due to gold coating. Dosimeters were selected in an effort to eliminate outlier data while retaining optical fibers within ±1 standard deviation of the mean value for subsequent use[10]. This process of selecting Ge-doped SiO_2 optical fibers was performed by irradiating large sample groups at a fixed dose as well as at a fixed dose rate (see Figure 2 A).

After the screening process, the selected fibers were found to be within ± 4.82% of the standard deviation (SD) of the mean TL value and were selected to minimize the variation in the TL yield of the fibers in subsequent measurements. As a result, from the initial 140 samples, only 105 samples were selected, reflecting that these had dopant concentrations within ± 5% variation (Figure 2.B). For fibers to be used in radiotherapy, the combined uncertainty should be no more than 5% in well-controlled radiotherapy, which is approximately the same order as the lowest dose difference that can be detected clinically[27].

The coating, post-coating irradiation and reading of the fiber optics were repeated a number of times to overcome the difficulties that were found in the gold etching. The aqua regia was used for gold etching. Unfortunately, there was a visible effect on the surface of the cleaned fiber (namely, a degree of opacity) due to the strong etching agent.

3.2. The glow curve

The sensitivity of a particular TLD material is defined as the TL signal (the peak height or TL intensity integrated over a certain temperature region) per unit absorbed dose and per unit mass. This sensitivity depends on the readout system, the heating rate and the light detection system used[6]. The effect of heating the fiber optics to stimulate the release of trapped energy after irradiation can be represented graphically as the total number of counts recorded against the temperature; this phenomenon is called the glow curve. The area under the curve represents the radiation energy deposited into the fiber. **(Figure 3)** shows the glow curve of a piece of optical fiber, which was used as a control non-coated fiber. The curve shows a single peak, as expected for the amorphous material, unlike the crystals of the TLD material, which show multiple peaks due to localized defect trapping.

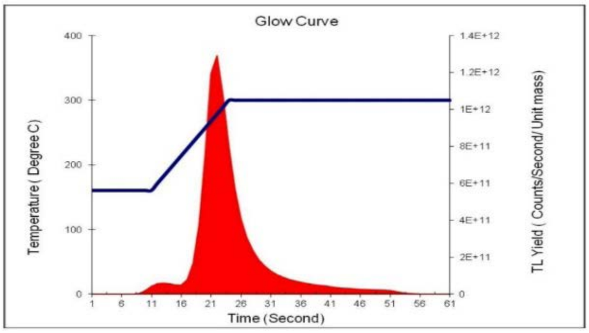

Figure 3: Glow curve of one of the optical fibers after irradiation with a 3Gy photon dose.

3.3. The TL yield of the optical fibers

The irradiation setup was previously described, with the TL yield represented as counts per second per unit mass of the pieces of the fibers. The resultant relation between the TL yield and the depth of the fiber in the phantom is graphically represented in **(Figure 4)**.

(Figure 5) shows the reproducibility of the results obtained by repeating the experiment. The following curve shows the results for a different set of optical fibers from the same manufacturer (CorActive, Canada) with the same diameter and dopant material. As shown in Figure 4.5, the sensitivity of these new optic fibers differs from that of the first fibers. Due to this variation, the whole selection process, including capturing the individual glow curves and recording the TL yield, was repeated.

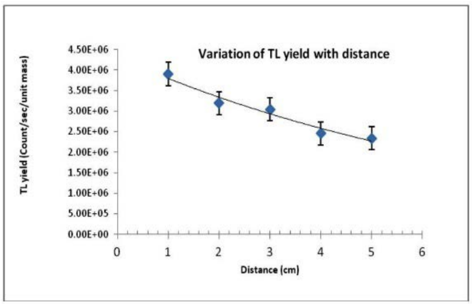

Figure 4: Relationship between the depth at which non-coated optical fibers are located in the phantom and the TL yield.

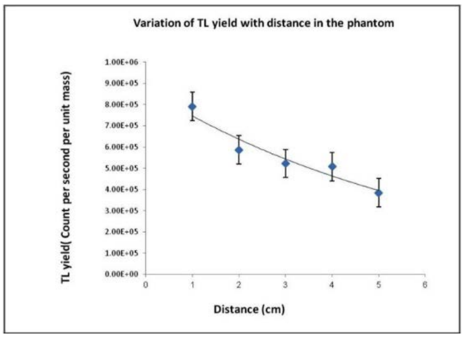

Figure 5: Illustrates the relationship between the distance at which non-coated optical fibers in the phantom were arranged and the TL yield.

As expected, the curve shows an approximate exponential dependency on depth in the phantom.

3.4. The enhancement of the TL yield of the gold-coated optical fibers:

(Figure 6) shows the TL yields of the coated and non-coated fiber optics and a comparison was made between them. At a gold coating thickness of 80 nm, the highest TL yield was reported. The lowest value was obtained for a gold thickness of 100 nm.

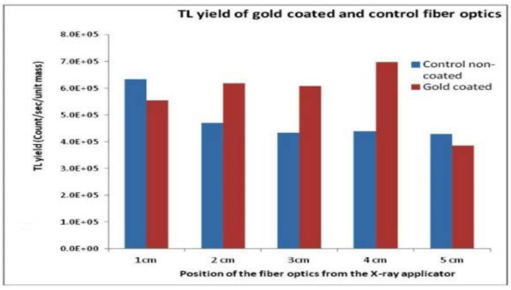

Figure 6: Shows the comparison between the TL yield of the gold-coated and control non-coated fiber optics.

The dose enhancement factor (DEF) was calculated using the TL yield of the gold-coated fiber optics and the corresponding control non-coated fibers in the same phantom step, i.e., at the same depth inside the phantom and at the same distance from the X-ray applicator. Equation (1) is used to calculate the dose enhancement factor:

DEF = (TL yield of gold-coated/TL reading of non-coated fiber) × 100 (1), **(Figure 7)**

Figure 6 clarifies that there is evidence of an increase in the dose due to the presence of gold coating the optical fibers. Figure 7 shows two exceptions to the coated fiber enhancement, which occur for 20 nm and 100 nm thick gold. The first thickness of gold may not be sufficient to observe any statistically significant DEF. In contrast, for the 100 nm thick sample, the inefficient removal of residual gold particles by chemical processes is a potential problem, leading to an inhibited TL yield. The enhanced TL yields obtained indicated that a large DEF may be obtained, for instance, at the interface between the synovial membrane surface and gold-coated contrast agents such as microspheres.

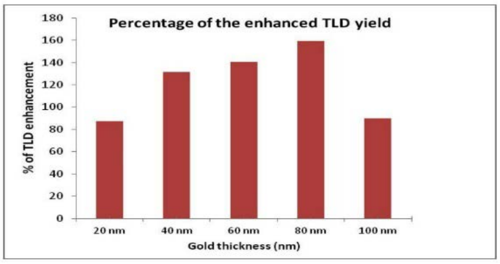

Figure 7: Shows the percentage enhancement in the TL yield due to the presence of gold.

Monte Carlo simulation (MCNPXv.2.6) was used to confirm the results of the experiment. There was an increase in the TL yield due to photoelectron production for the two phantoms used to resemble the inflamed joint in the case of iodine compared with the yield in the absence of iodine[26]. The importance of using optical fibers as radiation dosimeters has recently increased due to their higher chemical stability and relatively lower effective atomic number than those of films. Moreover, the addition of impurities or dopants to SiO_2 optical fibers enhances the radiation detection sensitivity[28]. In contrast to film dosimeters, optical fibers have a wide dynamic range. Fiber has been investigated by using different types of radiation, a range of energies and even different techniques. The performance of optical fibers has shown considerable potential for dosimetry applications in radiotherapy for both external beam and internal (brachytherapy). Concerning external radiotherapy, many workers have investigated fiber optics by using photon and electron beams[14] and for brachytherapy[29]. Moreover, the reproducibility and accuracy of this improved dose metric behavior need further study to be applicable in advanced and sophisticated modalities in radiotherapy, e.g., spatially fractionated radiotherapy (SFRT).

4. Conclusion

This in vivo dosimetry study at the micro scale was performed using fiber optics, which offers the advantage of high spatial resolution and low cost because this medium is reusable and reproducible. Dose enhancement can be used in radiotherapy to ensure that there is a high uniform dose to the tumor with a minimum dose to the normal surrounding tissue. The use of gold (Au) in radiation *in vivo* dosimetry is promising because it is a high-atomic-number material that is nontoxic and hence tolerable in the body. The difficulty of etching Au from the surface of fiber optics is only a disadvantage of this technique. Moreover, the results show enhancements with thicknesses of 40 nm, 60 nm and 80 nm, with the highest percentage of the dose enhancement occurring at an 80 nm thickness of gold, at 159%. There was a slight deviation from the enhancement at the first thickness of 20 nm gold, which may be due to the insufficient thickness for collecting the photoelectron products inside the micro dosimeter. In contrast, at a 100 nm thickness, residual gold particles almost certainly prevent the detection of the TL yield. The improved dosimetry technique used in this study could be applied in sophisticated radiotherapy modalities, such as spatially fractionated radiotherapy (SFRT).

Conflicts of Interest

The authors declare that there is no conflict of interest.

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List of abbreviations

Not applicable

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