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Energy dependence of novel inorganic scintillation based optical fibre sensors

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ABSTRACT

An optical fibre dosimeter based on a terbium-doped gadolinium oxysulphide (Gd\textsubscript{2}O\textsubscript{2}S:Tb) inorganic scintillating detector (ISD) was recently proposed for external beam radiation therapy (EBRT) dosimetry applications. Although it has demonstrated many promising characteristics, an energy dependence was found during percentage depth dose (PDD) measurements. In this study, the response of a Gd\textsubscript{2}O\textsubscript{2}S:Tb based ISD to superficial x-ray energies and 6 MV EBRT photon beams has been measured and compared to absorbed dose values generated using a Monte Carlo (MC) model of a superficial x-ray treatment unit and a clinical linear accelerator treatment head. The relationship between beam energy and the response of the scintillating phosphor was investigated for depth dose and beam profile measurements. An over-response was observed during physical measurements in the kV range that is indicative of an energy-dependent variation in scintillation efficiency of the Gd\textsubscript{2}O\textsubscript{2}S:Tb. This study indicates that this intrinsic energy dependence may result in a significant increase in signal at kV energies relative to MV irradiation, which was not accounted for in the MC model.

**Keywords:** Optical Fibre Sensors, Inorganic Scintillator, Radiation Therapy, Monte Carlo, Energy Dependence.
1. INTRODUCTION

In external beam radiation therapy, geometrical uncertainties from daily setup variation and internal organ motion affect the accuracy of the radiation dose delivered to the patient. These uncertainties are accounted for by adding a margin to the clinical target volume (CTV) to create the planning target volume (PTV). However, by adding these margins, the irradiated volume can increase significantly and the amount of healthy tissue exposed to high radiation doses can also increase. To address this, new radiation therapy treatments techniques such as intensity modulated radiotherapy (IMRT) and volumetric modulated arc therapy (VMAT) use small radiation field sizes and high dose gradients to deliver more conformal doses within tighter margins around tumours. However, any changes in the planned dose due to uncertainty encountered throughout the many steps of treatment planning and execution can affect the clinical outcome of the treatment significantly. As a result, several international organisations, such as the American Association of Physics in Medicine (AAPM), recommend performing in vivo measurements during treatment. This recommendation was the result of investigations following more than 7,000 major radiotherapy incidents between 1976 and 2007. Among these incidents are examples of both under-dosing – leading to a recurrence risk – and overdosing – causing toxicity and even death.

Currently, only a few systems are used for real-time in vivo dosimetry. These include diodes, metal-oxide semiconductor field effect transistors (MOSFETs), electronic portal imaging devices (EPIDs) and optical fibre-based dosimetry systems. Each of these systems come with their own advantages and limitations which strongly depend on the conditions of the measurement being considered. In recent times, optical fibre dosimeters (OFDs) have become an attractive alternative to conventional dosimeters for real-time dosimetry as they offer many desirable traits, such as: small dimensions, immunity to electromagnetic fields, linear response to dose and dose-rate independence. We recently proposed an OFD system using an inorganic scintillating detector (ISD) based on terbium-doped gadolinium oxysulphide (Gd$_2$O$_2$S:Tb) scintillator. This system has demonstrated promising characteristics when used in external beam radiation therapy settings. However, the system showed an energy dependence when measuring percentage depth dose (PDD).

The overall energy dependence of a detector is a combination of absorbed dose energy dependence and intrinsic energy dependence, which is the phenomenon whereby different beam energies delivering the same absorbed dose to the scintillating material detector produce different responses. The absorbed dose response for a Gd$_2$O$_2$S:Tb scintillator can be calculated using Monte Carlo (MC) simulation. However, the intrinsic energy dependence is difficult to model using conventional MC codes, though it can be measured or estimated based on empirical data.

The aim of this study was to investigate the scintillation mechanism responsible for the dose over-estimation of the ISD in terms of its intrinsic energy dependence using physical measurements and MC simulations. The response of the ISD to radiation doses using superficial x-ray energies and 6 MV photon beams was determined. MC models of the Xstrahl 200 treatment unit and an Elekta linac were developed using the MC software packages BEAMnrc and DOSXYZnrc to determine the absorbed dose to the ISD. The measured and MC simulated results were used to investigate the intrinsic energy dependence of the Gd$_2$O$_2$S:Tb scintillator.
2. METHODS & MATERIALS

2.1 Sensor design
The ISD was constructed using a polymethyl methacrylate (PMMA) plastic optical fibre. The core of the PMMA fibre was micro-machined to make a cavity 700 µm in diameter and 7 mm deep. The cavity was filled with the scintillating material and then sealed with an epoxy as shown in Figure 1. The scintillation material fluoresces on exposure to ionizing radiation, and the resultant emitted light propagates along a 25 m plastic optical fibre cable. The distal end of the optic cable was attached to a Hamamatsu multi-pixel photon counting module (MPPC C11208), set to measure in a 100 ms gate time and at 0.5 photon equivalent. The MPPC software was used to store the resulting signal for further analysis.

Figure 1. Schematic view of the inorganic optical fibre sensor and the Hamamatsu multi-pixel photon counting (MPPC) module.

2.2 Measurements

2.2.1 Superficial X-ray unit
The response of the ISD to low energy x-rays was evaluated using energies from 70 to 200 kVp delivered by the Xstrahl 200 kV superficial and orthovoltage treatment unit. The detector was positioned on the surface of a PTW (Physikalisch Technische Werkstatten, Freiburg, Germany) water tank, oriented perpendicular to the beam. For each beam energy, three measurements were taken with 1.0 min exposure times using a 10×10 cm² square cone. The average of all readings was used in further calculations and data analysis.

2.2.2 Linear accelerator
For the MV measurements, a 6 MV photon beam was used to deliver 100 MU using a field size of 10×10 cm² and dose rate of 600 MU/min. The ISD was placed at a depth of 5 cm in a solid water phantom with a standard source to surface distance (SSD) of 100 cm. An insert that mimicked the shape of a Farmer chamber was designed to provide an airtight cavity for the OFS when used in the solid water phantom.

2.3 Monte Carlo simulations
To accurately calculate the absorbed dose in the ISD, a MC model of an Elekta Versa HD linear accelerator (linac) and Xstrahl 200 were developed, using the MC software packages BEAMnrc and DOSXYZnrc. An accurate linac treatment head model can be achieved through an iterative tuning process\textsuperscript{16-23}. The development and validation of the Elekta linac has been described in our previous work\textsuperscript{4,6,8}. 

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2.3.1 Monte Carlo model of the Xstrahl 200

The Xstrahl 200 treatment head model was developed using the BEAMnrc package. The treatment head model consisted of several components including the x-ray tube, beryllium exit window, primary collimator, filter, ion chamber, and the 30 cm SSD 10×10 cm² square applicator. This model is depicted graphically in Figure 2. Four different beam energies including 70, 100, 125 and 200 kV were modelled. A phase space file was generated at the exit plane of the applicator for each simulation. This file acts as a pause in MC simulation as it stores the information about each particle in the simulation. Phase space files are typically used as an input into another MC simulation with a phantom, for dosimetry (dose deposition) purposes. DOSXYZnrc was used to model a 40×40 cm² water tank phantom in which dose was scored in 2×2×2 mm³ voxels.

The model was validated against measured depth dose curves and in-plane/cross-plane profiles at depths of 10 and 50 mm in a PTW BeamScan water tank using a PTW MicroDiamond detector. The model was considered to be tuned when simulated percentage depth dose (PDD) curves and profiles agreed with the measurements within specified uncertainty ranges (see Figure 3 & 4).

2.3.2 Monte Carlo simulation of the ISD

The EGSnrc package supplies the user with a large number of materials and compounds to be used in MC simulations. Users also have an option to create their own mixtures using elements and their fractional weight contributions. As the Gd₂O₂S:Tb was not available in the default PEGS4 data file, which includes the radiation interaction cross-section and stopping power data for all of the materials used in the simulation, the EGSnrcMP code was used to generate the PEGS4 data for the Gd₂O₂S:Tb scintillator. This was then used to model the sensitive volume of the detector surrounded by a layer of PMMA material. The detector was simulated on the surface of a water tank phantom for the kV energies using the BEAMnrc generated phase space files of 70, 100, 125 and 200 kV beams with a 10×10 cm² square applicator for a 30 cm SSD. Simulations were repeated with Gd₂O₂S:Tb scintillator replaced by water.
3. RESULTS & DISCUSSION

3.1 Monte Carlo model of the Xstrahl 200

An accurate MC treatment head model of the Xstrahl 200 was achieved for 70, 100, 125, 200 kV energy beams. The simulated and measured PDD curves, normalised to 10 mm depth, are presented in Figure 3. The in-plane (IP) and cross-plane (CP) profiles at depths of 10 and 50 mm for 100 kV irradiations are shown in Figure 4. All profiles were normalised to the central axis and the data are presented with fitted lines. A dashed line was used to represent 80% FWHM, within which the measured and simulated profiles were compared. For all energies, the mean percentage differences between the measured and simulated data shown in Figures 3 and 4 were below 1%.

![Comparison of the MC simulated and measured PDD curves normalised at 10 mm depth for all the beam energies investigated in this study.](https://ebooks.spiedigitallibrary.org/conference-proceedings-of-spie)
3.2 ISD energy dependence

Figure 5 illustrates the comparison between the measured ISD response and the simulated dose to the scintillating material in the MC model at different energies. The measured and simulated responses are normalised to the value at 6 MV. There is an obvious over-response in the measured signal in comparison to the simulated absorbed dose values. This overestimation, relative to the 6 MV data, is greatest for the 200 kV beam, with a relative response 2.8 times the simulated value, and lowest for the 125 kV beam, with a relative response 2.5 times the simulated value.

As the MC model simulates dose deposition from photon interaction events governed by the atomic cross-sections and photon-matter interaction probabilities which depend on the photon energy, the effective atomic number ($Z_{eff}$) and density of the material of the detector, it can only account for any dependence of the detector on absorbed dose. The mismatch between the measured and simulated data, therefore, highlights the model’s inability to account for an intrinsic dependence of the scintillation efficiency of the Gd$_2$O$_2$S:Tb on photon energy.

This result confirms the necessity for a full analysis of the response of ISDs at constant absorbed dose using different photon energies. The use of radiation sources with energies within the 200 kV to 6 MV range is paramount for future investigations. A full characterisation of this energy dependence and generation of a correction model would be an essential future study to ensure accurate correction factors for applications such as in-vivo dosimetry.
4. CONCLUSIONS

The response of a Gd$_2$O$_2$S:Tb ISD to radiation doses using superficial x-ray energies and 6 MV photon beams was measured. The measured responses were compared to absorbed dose values generated using MC models of a superficial x-ray treatment unit and a clinical linear accelerator treatment head to investigate the relationship between beam energy and the response of the ISD. The over-response of this detector during physical measurements in the kV range indicates the presence of a photon-energy-dependent variation in scintillation efficiency of the Gd$_2$O$_2$S:Tb scintillator. The relative measurements made in this study indicate that this intrinsic energy dependence results in significant increase in signal at kV energies.

In order to utilise such ISDs in clinical dosimetry applications, the absorbed dose and intrinsic energy dependences of the scintillating medium must be separated and fully characterised. Future work will pursue fully separating the well-understood absorbed dose dependence from the undetermined intrinsic energy dependence of the Gd$_2$O$_2$S:Tb phosphor to ensure accurate dosimetry of the detector over a range of energy applications.

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