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Paper

Optical performance studies of an all-polymer air-core scintillation dosemeter for brachytherapy

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Abstract

Plastic scintillation dosemeters have gained significant interest for *invivo* dosimetry in high-dose rate brachytherapy (BT) due to their favourable dosimetric properties. However, their clinical utility is limited by Cerenkov radiation, which can contribute over 50% of the signal, depending on the source position. The current dosemeter based on silica air-core (AC) light-guide was proven to be highly accurate; however, its high light loss and its mechanical rigidity limit its use for *invivo* BT dosimetry with flexible applicators. In the present work, a novel flexible all-polymer dosemeter with silver-coated polytetrafluoroethylene (Ag-PTFE) light-guide was built and compared to a solid-core light-guide dosemeter (standard dosemeter), using Geant4 Application for Tomographic Emission simulations. A reduction of the Cerenkov noise in the signal of this AC dosemeter was found below 0.3%, independently of the source position. On the other hand, the light collection efficiency was found to be ∼40% smaller than in the standard dosemeter. We show how it is possible to further reduce this difference to ∼20% and discuss the optimal design of this all-polymer Cerenkov-free dosemeter.

Introduction

Invivo plastic scintillation dosemeters for high-dose rate (HDR) brachytherapy (BT) have drawn lots of attention in the last years due to their notable dosimetric properties. Their limited clinical use is due mainly to the presence of Cerenkov light produced by electrons propagating at velocities higher than the speed of light in the plastic. A recent review by Veronese *et al.* [1] addresses the different techniques of Cerenkov reduction, among them the air-core (AC) method, in which the solid plastic light-guide is replaced by an AC light-guide, currently made of internally silvered silica [2]. This solution was reported to have excellent dosimetric accuracy compared to other techniques, like the spectral discrimination method [3], and many relevant advantages, such as less complex calibration, no warm-up time, and shorter acquisition time. However, this dosemeter is reported to be mechanically rigid due to the silica light-guide and the use of a large photomultiplier tube (PMT) used for its readout. It also features high light loss, reported to reduce the signal by a factor of up to 10, compared to the standard dosemeter with solid-core light guide.

In the present work, an improved AC concept was developed for a scintillation dosemeter aimed for *invivo* prostate BT dosimetry. This is based on an Ag-PTFE light guide of 15 cm length, corresponding to the size of a prostate BT radiation field. The AC light-guide is coupled, on a one side, to a 5 mm scintillating fibre and on the other side, to a long plastic optical fibre, read out by a silicon photomultiplier (SiPM). In the studies reported in reference [4] addressing this dosemeter, Cerenkov-to-signal (C/S) ratio was first assessed in fibre bundles using simulations and a dedicated experimental setup for the precise measurement of scintillation and Cerenkov light induced by different radioactive sources. The C/S ratio was found to be ∼1% from scintillating fibres, when exposed to beta and gamma radiations in the energy range 1–2 MeV. The performance of the AC Ag-PTFE light guide dosemeter was then studied and compared to a standard dosemeter with a plastic-core light guide, in a prostate BT scenario using a ^{60}Co source. The C/S

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ratio in the standard dosemeter was found to be up to 53% when the source was moved from the scintillating fibre position to positions where the light-guide was fully exposed to the radiation field in the prostate. For the AC Ag-PTFE dosemeter, the maximum C/S ratio at similar source positions was found not to exceed 0.3%. However, light collection in the AC dosemeter was found to be ~40% smaller than in the standard dosemeter, mainly due to the light-loss at the plastic-air interface of the AC dosemeter. Although high-gain SiPM readout may compensate for this reduction in the signal size, optimisation of the optical performance of the AC dosemeter is required for high-resolution dose measurement.

In the present paper, scintillation light attenuation in the standard and PTFE light guides is studied, as well as the photon collection efficiency of the fully silver-coated standard and AC dosemeters, using Monte Carlo simulations.

Material and methods

The present study builds upon the previously developed flexible scintillation dosemeter incorporating an Ag-PTFE AC light guide, in place of the plastic light guide that would be exposed to the radiation field, as detailed in our published paper [4]. In the present work, the performance of the Ag-PTFE AC dosemeter was evaluated using GATE (Geant4 Application for Tomographic Emission) [5] simulations in a high dose-rate prostate BT scenario, in a similar way as described in reference [4], with the focus on characterising the light attenuation in the light guides and studying the impact of silver-coating of the scintillating fibre on the light collection efficiency of the dosemeters. Both studies were not addressed in the mentioned publication; thus, further studies on the optical performance of the dosemeters are needed.

The optical Monte Carlo simulations were performed using only the optical physics processes, including scintillation photon generation, absorption, Rayleigh scattering, and boundary interactions such as reflection and refraction. Cerenkov emission and ionising interactions were not included, as only optical photon transport was studied. The optical properties of the materials (refractive indices, absorption lengths, and reflectances of the scintillating fibre, PTFE capillary, and silver coating) were defined based on manufacturer's data and values from the literature. Each simulation consisted of 10^8 optical photons emitted isotropically from a punctual optical source, placed in front of the scintillating fibre. This was repeated ten times to determine the mean and the standard deviation of the light collection efficiency. A detailed description of our GATE simulations configuration, validation procedure, and physics models used in this work can be found in our previous publication [4].

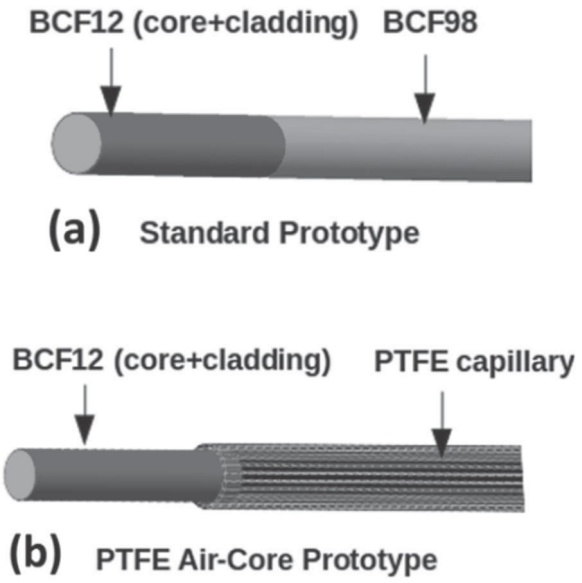

Figure 1. Drawing of the two dosemeter prototypes simulated in GATE, (a) standard prototype, (b) Ag-PTFE AC prototype.

The fibres used are from Saint-Gobain Crystals [6], so the nomenclature of the company is used here. The scintillating fibre (BCF12) and the clear optical fibre or light guide (BCF98) are both made out of a polystyrene (PS) core with a refraction index $n = 1.6$, covered with a PMMA cladding of 1.49 refraction index. Two dosemeter prototypes were simulated according to the design shown in Fig. 1. The first one, called standard prototype, is composed of 5 mm length scintillating fibre (BCF12) coupled with optical cement to 15 cm length solid-core plastic light-guide (BCF98). The second prototype, called Ag-PTFE AC, is composed of 5 mm length scintillating fibre (BCF12) coupled with optical cement to a 15 cm length Ag-PTFE capillary. This capillary of 1.26 mm external diameter and 1.0 mm internal diameter, from Eco Polymer [7], was coated in-house, at the *Instituto de Física Corpuscular*, by silver evaporation under vacuum. A small part (0.5 mm) of the BCF12 fibre is introduced inside the PTFE capillary to ensure mechanical strength and high light collection in the light guide. In both prototypes, the scintillating fibres were totally coated with 200 nm of pure silver, similarly to that produced on the PTFE capillary (see Fig. 2). The total diameter of the silver-coated AC prototype is 1.2602 mm, a dimension allowing it to slip into the BT afterloader capillaries of typically 1.3 mm diameter [8].

The light attenuation in the BCF98 light-guide and the PTFE capillary was first simulated to assess the

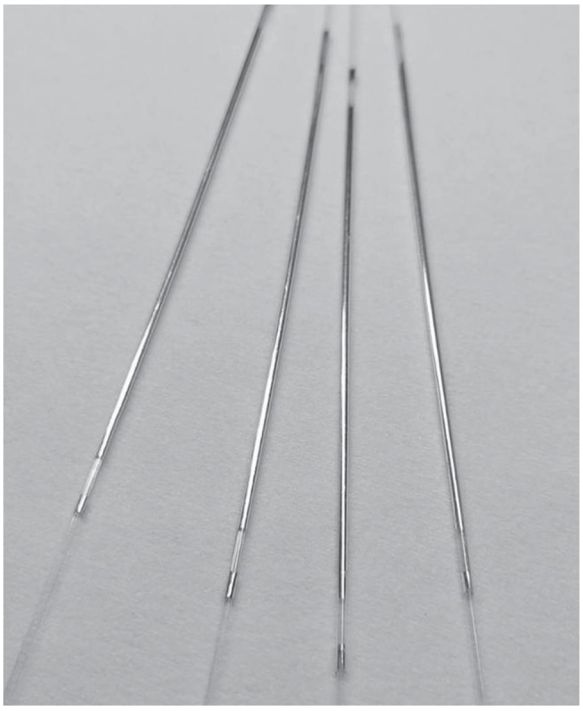

Figure 2. Photograph of Ag-PTFE light-guides used for the AC dosemeter.

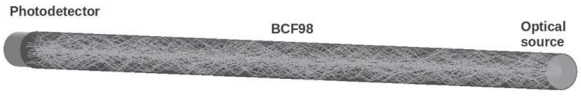

Figure 3. Drawing of the light attenuation simulation in a BCF98 fibre, the light cone at the entrance face of the fibre is shown.

goodness of the GATE optical simulations by comparison with the manufacturer data. A punctual light source, with a spectrum similar to the BCF12 scintillation light provided by Saint Gobain Crystals [6], was simulated and placed at one end-face of the fibres of up to 3 m length. The light is made to propagate into the fibres core through a conic emission, as shown in Fig. 3, allowing the same number of photons to be propagated into the two light guides under study. The number of photons reaching the opposite end-face of the fibres is compared to the initial one, and the attenuation length of the fibres, corresponding to $1/e$ of the initial photon flux, is drawn.

On the other hand, to estimate the light collection efficiency of the two dosemeter prototypes fully coated with silver (i.e. scintillating fibres and light-guides), a punctual optical source emitting light isotropically was placed at the centre of the scintillating fibre to simulate emission of scintillation light, as shown in Fig. 6a of reference [4]. The light collection efficiency is drawn

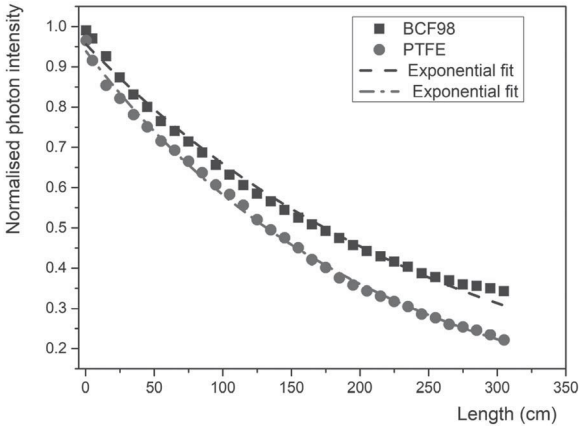

Figure 4. Normalized photon intensity as a function of the fibre length for the solid-core light-guide (BCF98) and for the non-coated AC light-guide (PTFE), the exponential fit function is drawn for each case.

for both dosemeters comparing the light detected in the photosensor coupled to the light-guide to the light emitted by the source.

Results and discussion

In Fig. 4, the normalized photon intensity in the standard solid-core fibre (BCF98) and the non-coated PTFE AC light guide is represented as a function of the fibre length. An exponential attenuation is observed in both fibres, with an attenuation length of 270.3 ± 4.4 cm for the BCF98 fibre. This is compatible with the measured attenuation value of 270 cm quoted in the manufacturer's data sheet for BCF12 fibre, whose base material is similar to BCF98 [6]. This indicates our GATE optical simulations model and physical processes used to describe precisely the light propagation in the fibres. For the PTFE light guide, the attenuation is stronger, as expected, with the attenuation length being 212.8 ± 2.1 cm, i.e. 21% more attenuation for long fibres compared to the standard optical light guide. This value needs confirmation from laboratory measurements, as there are no experimental values available from the manufacturer. Indeed, the light propagation in the capillary, may follow a different pattern than in the BCF98, PTFE being a diffuse reflector with a refractive index higher than air. The attenuation is mainly due to the refracted light through the capillary's thin walls, most of which may be recovered by an external silver coating.

To validate experimentally the optical simulations of the PTFE light guide, we plan to use an experimental setup consisting in a light source (light emitting

diode) with an emission spectrum like that of BCF12 fibres, and a calibrated PMT. PTFE fibres of different lengths will be coupled to the light source, whose emission intensity is known, and will be read out using the PMT. The attenuation coefficient will be obtained by comparing the input and output intensities as a function of the fibre length. BCF98 fibres will be used to adjust the experimental setup. This measurement will additionally enable the study of the impact of uncertainties on the input parameters of the simulations, such as the reflectance of the PTFE light guide, on the simulated attenuation coefficient.

The photon collection efficiency of the fully silvered dosemeters is shown in Fig. 5 as a function of the light-guide length. We can observe in this figure that the light collection efficiency is practically constant for light-guide lengths of up to 15 cm, which is the maximal size of the radiation field in prostate BT. Furthermore, the addition of a silver coating to the scintillating fibre induces in the AC dosemeter an increase in collection efficiency of 48%, from (14.6 ± 0.2)% (AC non-coated BCF12) to (21.6 ± 0.2)% (AC coated BCF12). For the standard dosemeter, this increase of collection efficiency is of 12%, i.e. from (24.18 ± 0.12)% (ST non-coated BCF12) to (27.2 ± 0.2)% (ST coated BCF12). For the solid-core optical fibre BCF98, this 12% increase in light collection is exclusively due to the specular reflecting walls of the scintillating fibres, which reflect back the refracted light into the fibre core. Indeed, there is no light loss in the interface between the scintillating fibre BCF12 and the solid light guide BCF98, as this propagates in the same medium. In the AC dosemeter, most of the light recovered by the additional coating on the scintillating fibre is due to the silver-coated en-face of this fibre which reflects back into the PTFE capillary the photons lost in the PS-air interface. So, most of the light gain in the AC dosemeter induced by coating the scintillating fibre stem from the recovery of the photons lost at the plastic-air junction.

The difference in light collection efficiency of the AC and the standard dosemeters is thus reduced from ~40% (with no coating of the scintillating fibre) to ~20% for the fully silvered dosemeters. This difference can be further improved by applying an internal silver coating to the PTFE light guide, as outlined in reference [4]. More importantly, signal amplification can be obtained with a high-gain SiPM, with stabilisation against variations of the temperature. This stabilisation process has indeed been investigated in [9], in which it was shown that a stabilisation of the SiPM gain of better than 0.2% per °C was obtained using a voltage-based compensation method.

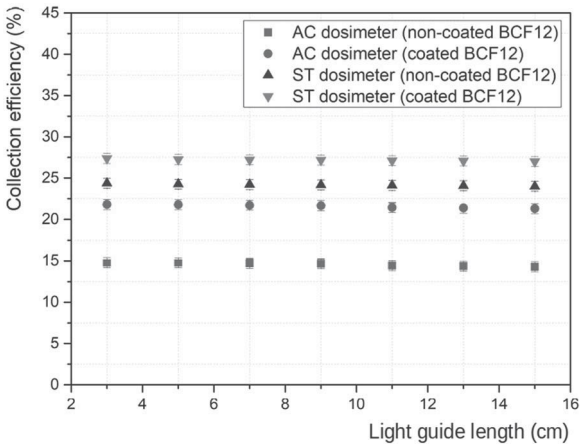

Figure 5. Light collection efficiency as a function of the light-guide length for the standard and AC dosemeters, with coated and non-coated scintillating fibre BCF12.

Conclusion

In the present paper, optical performance studies of the novel all-polymer AC dosemeter prototype developed for HDR prostate BT are described. These aimed at improving the dose signal magnitude of this dosemeter compared to the standard dosemeter with a plastic-core light-guide, whose main disadvantage is its lack of accuracy due to its high Cerenkov optical noise during HDR BT. We have first shown that the light attenuation in the standard BCF98 light-guide as a function of the fibre length follows an exponential pattern, with an attenuation length of 270.3 ± 4.4 cm, compatible with the value provided by the manufacturer. This result indicates reliable GATE optical simulations. The attenuation length of the non-silvered PTFE light guide is found to be 212.8 ± 2.1 cm, i.e. 21% smaller, as expected. The light collection efficiency of these dosemeters was then assessed before and after coating of the scintillating fibre, as to better understand the magnitude of the light loss at the fibre-air interface in the AC dosemeter. This is indeed where most of the photons are lost. The silver coating of the scintillating fibre increases by 12% the light collection efficiency of the standard dosemeter, whereas it increases by 48% that of the AC dosemeter. This reduces the difference in the dose signal magnitude of the two dosemeters from 40% to 20%. Further optimisation of the light collection may be obtained with an internal silver coating of the AC light guide. However, for the optimal design and construction of an all-polymer Cerenkov-free high-resolution dosemeter, most important will be the use of a high-gain SiPM for the dosemeter readout, with gain stabilisation against variations of temperature.

The experimental validation of the optical simulations of the PTFE light-guide is currently in progress and will be reported in a forthcoming publication.

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