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Development of a new 3-dimensional scintillating detector for patient treatment quality control in pencil beam scanning proton therapy

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Abstract. In this work, we developed a three-dimensional (3D) scintillation system, whose fast response and high sensitivity allow the measurement of pencil beam (PB) characteristics (position, energy and intensity in terms of monitor units - MU) for pencil beam scanning proton therapy. The system consists of a $10 \times 10 \times 10$ cm^3 scintillator cube that produces visible light when irradiated with PBs. A high-speed camera records the scintillation distribution and a mirror positioned at 45° to the cube allows visualization of two orthogonal faces of the cube. The measurements demonstrated the ability of our system to measure beam characteristics for intensities as low as $2 \cdot 10^{-3}$ MU in a single irradiation. Standard deviations of less than 300 µm were found for the X and Y PB positions, of approximately 150 keV for energy and of less than $5 \cdot 10^{-3}$ MU for intensity. These measurements were then successfully used to verify the compliance of the PBs delivery with the treatment plan, thus making our system a fast and efficient verification tool.

1. Introduction

Pencil beam scanning Proton therapy has a number of advantages, in particular with regard to the dose deposition profile of charged particles. It consists of scanning the tumour volume with a finite number of pencil beams (PBs) whose energies and positions allow a uniform dose distribution. However, with the IBA Proteus®ONE system [1], the accuracy of the delivered pencil beams in terms of delivered monitor units (MU) requires that the PBs be divided into multiple pulses of 7 µs delivered at a frequency of 1 kHz. These delivery constraints make it difficult to perform patient-specific quality control (QC) based on the verification of the delivered PB characteristics (position, energy, intensity in terms of MU) on a PB-by-PB basis. To address this issue, scintillators are very promising due to their advantageous properties: spatial resolution, real-time measurement, shape versatility [2-7]. Developments have been made in the field of proton therapy with plane scintillators [8], and the Lynx system is commercially available for 2D relative dosimetry and daily quality assurance (IBA dosimetry, Schwarzenbruck, Germany).

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Developments have also been made with liquid scintillators to measure the range and the position of proton spots [9,10]. Thanks to fast cameras, recent studies have brought scintillation dosimetry into the field of real-time PB characterization, in particular to perform range and dose rate measurements [11,12]. In this work, we developed a three-dimensional (3D) scintillation system, called SCICOPRO (for SCIntillation for treatment COntrol in PROton therapy), whose fast response and high sensitivity allow treatment QC by measuring, in a single irradiation, the position, energy and intensity of the delivered beams on a PB-by-PB and even pulse-by-pulse basis.

2. Materials and methods

The system developed in this work, shown in Figure 1, consists of a scintillator cube of $10 \times 10 \times 10$ cm^3, that produces visible light when irradiated with PBs. A high speed camera records the scintillation distribution and a mirror placed at 45° to the cube allows to visualize two orthogonal faces of the cube, and thus two orthogonal projections of the scintillation distribution, on a pulse-by-pulse basis. The synchronization of the camera with the pulse delivery ensures that each pulse is captured without any beam loss.

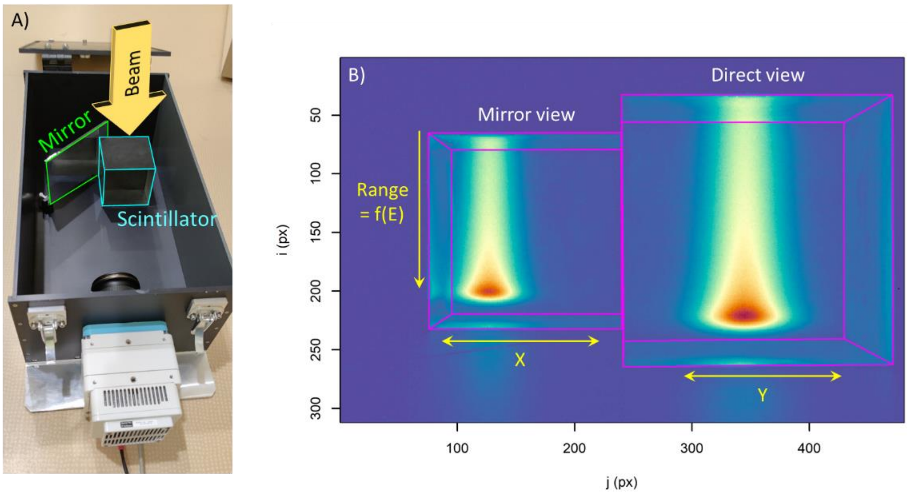

Figure 1. A) SCICOPRO setup consisting of a $10 \times 10 \times 10$ cm^3 BC-412 plastic scintillator, a mirror oriented at 45° to the cube and a fast camera. B) The images recorded by the camera consist of a direct projection and a mirror-reflected projection of the scintillation distribution produced by each pulse in the scintillator.

Pulse images were individually corrected for background signal and hot pixels (a parasitic signal caused by scattered radiation hitting the camera sensor directly). In this application, the PBs were delivered far enough away from the sides of the scintillator to avoid any bias caused by optical reflections at the edge of the scintillator. Analysis of these images provided the position and intensity of the Bragg peak in both projections. The SCICOPRO measurements were calibrated against the Proteus®ONE ionization chamber measurements recorded in log-files because, to our knowledge, this is the only detection system capable of providing all pulse characteristics for cross-calibration.

In a first step, SCICOPRO performance was evaluated on 729 PBs at fixed intensities of 0.02, 0.1 and 1 MU. QC of patient treatment plans was then performed with SCICOPRO for 7 irradiation plans: one delivering a uniform dose of 0.8 Gy in a 5 cm diameter sphere and 6 patient treatment plans. The sphere irradiation plan was delivered, with a nominal positioning, but also with 1°

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rotations of the treatment table to evaluate the ability of SCICOPRO to detect potential treatment delivery problems, in this case a positioning error. The PB characteristics were calculated from the pulse characteristics, where the position and energy are the average of the intensity-weighted pulse positions and energy, and the PB intensity is the sum of the pulse intensities. Finally, the measured characteristics of the delivered PBs were compared with the characteristics of the planned PBs. A global agreement factor of the treatment delivery was defined as the proportion of PBs whose characteristics matched the planned ones, with a tolerance of 1 mm for position and 5 % for intensity.

3. Results

The intensity of all PBs of the 7 treatment plans evaluated in this study ranged from 0.02 to 4.1 MU. However, splitting these PBs into several pulses resulted in the delivery of pulses of much lower intensity, all between approximately $2 \cdot 10^{-3}$ to $150 \cdot 10^{-3}$ MU, which drastically reduced the measurement dynamics. It should be noted that SCICOPRO demonstrated its ability to measure pulse characteristics at these very low intensities. Standard deviations of less than 400 µm in X and Y position, of about 180 keV in energy and of less than $0.65 \cdot 10^{-3}$ MU in intensity were measured on the pulses. For PB characteristics, calculated from pulse characteristics, this corresponds to standard deviations of less than 300 µm and 150 keV, regardless of PB intensity. The standard deviation of the measured intensity, on the other hand, was found to depend on the planned intensity and was of about $1 \cdot 10^{-3}$ MU for 0.02 and 0.1 MU and about $5 \cdot 10^{-3}$ MU for 1 MU. This is due to the higher number of pulses required to achieve 1 MU than 0.02 and 0.1 MU.

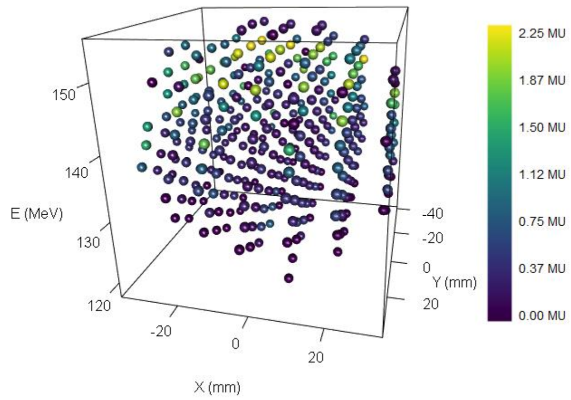

Figure 2. PBs characteristics measured with SCICOPRO for the irradiation plan producing a uniform dose distribution of 0.8 Gy in a 5 cm diameter sphere. Each PB is represented spatially by its X and Y positions and energy (vertical axis). The PB intensity is represented by the colour scale. For clarity, only the measured characteristics are shown here as they closely match the planned characteristics.

An example of PB characteristics reconstructed from pulse characteristics measured with SCICOPRO is shown in Figure 2. This representation, which spatially represents the position and the energy, and in the colour scale the intensity has the interest of displaying the information of all PBs of a treatment, complementary to the 3D dose distribution, which may hide the delivery details. For all the treatment plans tested, SCICOPRO made it easy to verify that the delivered PBs matched the treatment plan. More than 99 % of the PBs were within a tolerance of 1 mm for position and 5 % for intensity. When a 1° rotation of the treatment table was introduced, this proportion fell to 86 % or less, confirming the ability to detect positioning errors.

4. Discussion

The ability to measure proton spot characteristics has been demonstrated previously with liquid scintillators, but at a limited rate of 85 frames per second [9,10]. On the other hand, recent advances in high-speed cameras have been used to perform dose rate and proton range measurements [11,12]. With our system, we demonstrated the feasibility of verifying the characteristics of all PBs of a treatment in a single irradiation, even at very low intensities. The treatment verification performed in this study provides complementary verifications to 2D or 3D dose distributions integrated over the entire treatment, as it can highlight some problems that may be more difficult to identify in integrated measurements.

5. Conclusion

We developed a new scintillating system capable of measuring pulse characteristics at very low intensity (down to $2 \cdot 10^{-3}$ MU) and high frequency (1 kHz), overcoming the delivery constraints of the Proteus®ONE system. It is a very efficient QC tool thanks to its geometry, which allows all PB characteristics of a treatment to be determined in a single measurement.

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