PROCEEDINGS OF SCIENCE

A 16-sensor prototype for brachytherapy in vivo dosimetry characterization.

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The ORIGIN project (Optical Fiber Dose Imaging for Adaptive Brachytherapy) targets the production and qualification of a real-time radiation dose imaging and source localization system for both Low Dose Rate and High Dose Rate brachytherapy treatments. This goal will be achieved through a 16-fibre sensor system. Each fibre tip has been engineered to house a small volume of scintillating material to allow for measurements of the delivered dose. The instrument is based on Silicon Photomultipliers detectors, with a solution fully qualified on a single fibre prototype and currently being scaled up through the use of the CITIROC1A ASIC by WEEROC, embedded in the FERS-DT5202 scalable platform designed by CAEN S.p.A. The key features for a system such as ORIGIN, which aims to perform dose measurements in a clinical environment, are fibre response uniformity, system stability, high sensitivity, and perfect reproducibility. The commissioning of the 16-channel dosimeter system in laboratory conditions, with an X-ray cabinet, demonstrated reproducibility of measurements with deviations below 1% after the equalization procedure of the 16 sensors. Finally, the system performance, evaluated in clinical conditions (High Dose Rate centre, Belfast Hospital), allowed for valuable insight into the possible systematics which are present in the current system while simultaneously corroborating the validity of the equalization procedure.

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1. Introduction

BrachyTherapy (BT) treatments consist of highly specialized radiotherapy procedures during which the radioactive source is implanted into the patient's body, close to the cancer-affected area. This treatment is notably used for prostate and gynecological cancers, where the proximity of organs at risk limits the possibility of relying on external beams. According to the average activity of the source in use, clinical treatments are categorized as either Low Dose Rate (LDR-BT, rates in the 0.4-2 Gy/h range) or High Dose Rate BT (HDR-BT, rate > 12 Gy/h). Standard BT procedures do not implement in-vivo dose verification as they rely on pre and post-treatment computed tomography, ultrasound imaging, and dose calculation via a computerized Treatment Planning System (TPS) based on the TG43-U1 protocol [1]. Indeed, in-vivo dosimetry would instead allow better control over the dose delivered to the patient and, thus, the most precise execution of the chosen treatment plan. Therefore, in the past decades, much work has been done to develop systems that could provide in vivo dose verification. The ORIGIN [1] project (Optical Fiber Dose Imaging for Adaptive Brachytherapy) aims, exactly, to provide real-time dose measurement during the treatment and to perform a precise localization of the radiation source. A comprehensive overview of the specifications, together with the qualification procedure and first results achieved in HDR clinical conditions of the 16-channel system, will be described in this work.

2. Material and methods

The basic element of the dosimeter system consists of a Poly Methyl MethAcrylate (PMMA) optical fibre with a scintillating tip (sensor in the following), and a Silicon PhotoMultiplier (SiPM) (detector in the following) used to detect the light emitted by X- or γ-ray interacting with the scintillating material. Two scintillating materials are considered in the project: Gd_2O_2S:Tb (Gadox)[2, 3], emitting at 545 nm, and $1Y_2O_3$:Eu + $4YVO_4$:Eu (YVO)[3, 4], emitting at 600 and 650 nm. Both scintillating materials have similar decay times of the order of $\sim 500\ \mu$s. Thus, a single interaction results in the emission of a sequence of single photons distributed in time, opening the possibility of performing dosimetry by pulse counting. The multi-fibre system was developed using 16 fibre sensors coupled to SiPMs (1x1 mm^2 from Ketek[2] for the HDR measurements), with front-end and readout board based on CAEN FERS (DT5202)[3] housing the CITIROC1A [5] by WEROC, a 64-channel front-end ASIC. Hence, the system can trigger at the single photonelectron level with a maximum counting rate of 20 MHz. For the HDR setting, the chosen scintillating material is YVO due to its better characteristics for HDR [6].

3. 16-channel system characterization

After successfully verifying that the single-fibre dosimeter system matches the project specifications for both LDR and HDR brachytherapy, we then moved to the 16-channel dosimeter system

[1]The ORIGIN project is an initiative of the Photonics Public Private Partnership (www.photonics21.org) and has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement n. 871324.

[2]https://www.ketek.net/sipm/sipm-products/wb-series/

[3]https://www.caen.it/products/a5202/

testing both in the laboratory and in the clinical environment. Fig. 1 shows that the data from clinical HDR measurements (single fiber) are TG43-U1 complaint.

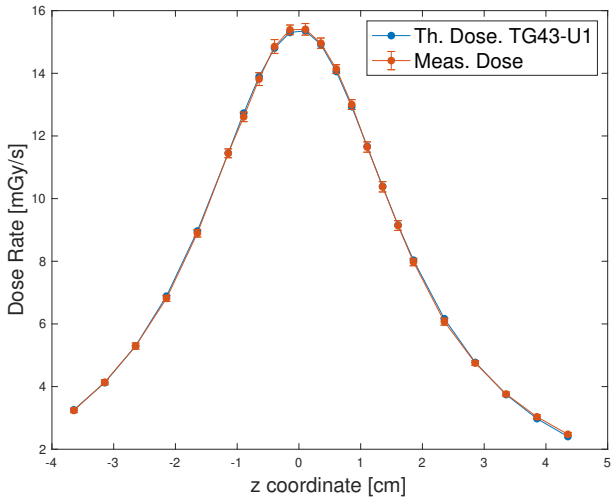

Figure 1: Dose rate measured data compared TG43-U1 dose for a single fiber.

3.1 16-channel system laboratory characterization

The 16-channel system was characterized in the laboratory with an X-ray cabinet to avoid radiation protection issues and to operate the system in stable and reproducible conditions. The fibre tips were irradiated with the X-ray beam, providing single photon counting rates up to a few MHz, typical rates of HDR-BT. The non-uniformity of the fibre response was measured to be at the level of 16 %, where dis-homogeneities due to fibre connections and the alignment to the SiPM contributed to an overall 11 % variation. An Equalization procedure, which takes into account all of these contributions, was built from a scaling factor measured by the response of the fibres uniformly irradiated by the X-ray beam. Fig. 2 shows the measured raw counting rate at different X-ray beam currents in the left panel and the scaled one in the right panel with a residual non-uniformity below 1%. The inset reports the relative standard deviation of the slopes of each channel curve: it is 15% in the left panel and less than 1% in the right one.

3.2 16-channel system clinical characterization

The clinical evaluation of the system for the HDR-BT was performed at the Queen's University Hospital (Belfast, Ireland). Sensors were positioned in an equivalent water phantom with cylindrical symmetry with an ^{192}Ir source moving along the cylinder axis (see Fig. 3). The Phantom was immersed in a water tank. Sensors were positioned at different distances from the phantom axis (see Fig. 3), along which the source was moved up to 10 cm distance from the sensor plane with different steps (see Fig. 3). Data refer to eleven sensors only because five were damaged during the assembly. The measurement set allowed us to reconstruct the dose fall-off shown in Fig. 4 before and after the application of the scaling factor. In Fig. 4, only the fibres at 1 cm and 1.5 cm distance

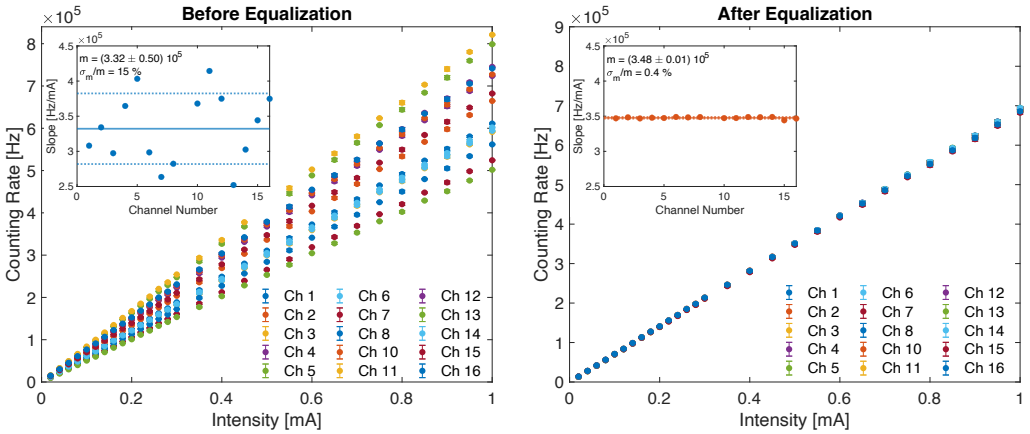

Figure 2: X-ray intensity scan. Left panel: Raw data, before the application of the equalization factor. Right panel: Data after the application of the scaling factor.

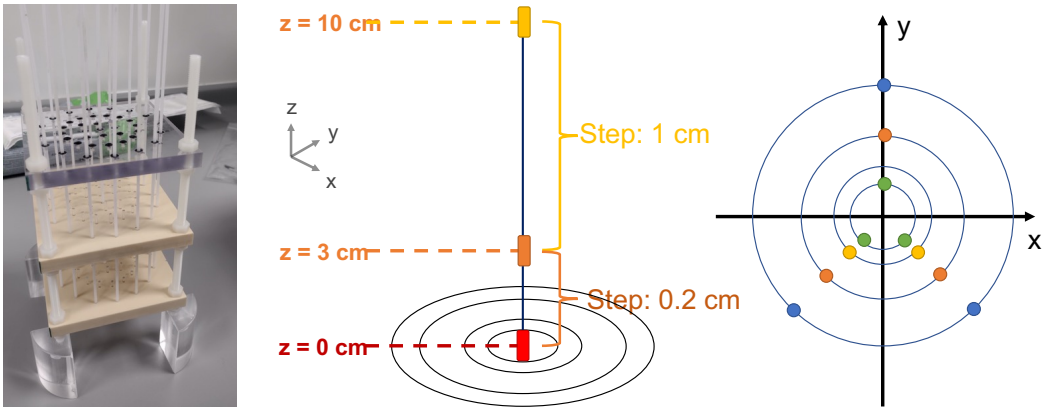

Figure 3: On the left: a picture of the phantom. In the middle: a schematic view of the source positions during the measurements. On the right: a schematic view of the fibre positions on the x-y plane.

from the centre are reported. As visible in the first two panels of Fig. 4, the scaling factor did not work as expected from the laboratory test. Thus, we set out to investigate the causes.

Given the good quality of the laboratory equalization, we considered possible sources of systematics identifying a potential weakness in the positioning of the fibre tips along the z-axis (see Fig. 3). To investigate this possibility, we implemented a correction method approximating at order zero the dose fall-off as $1/r^2$ and presuming a systematic shift (Δz) in the tip position. We calculated the Δz values for the fibres on the circumferences closest to the centre (1 cm and 1.5 cm) to take advantage of the higher sensitivity and used them to correct the source-sensors positions related to the measured counting rate values. The right panel of Fig. 4 shows the result of this correction. A residual difference between the corrected curves can be attributed to the fact that the correction method is based on a rough approximation of the TG43-U1 calculated dose fall-off, which also takes into account the angular dependence of radiation emission, the cylindrical shape of the source, the attenuation of gamma rays in water and the dose built-up due to scattering.

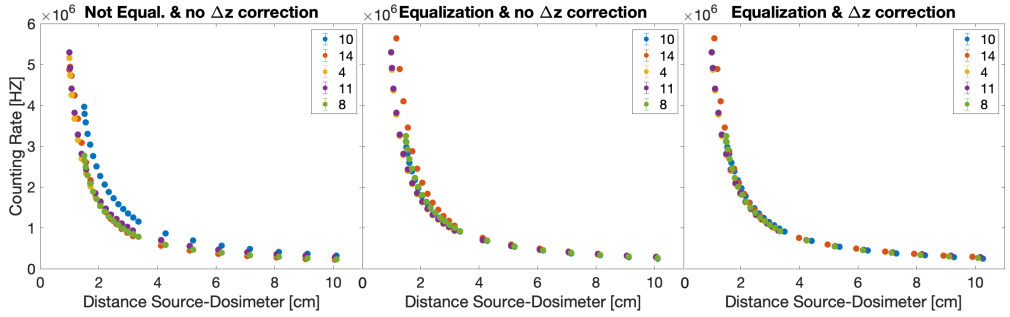

Figure 4: The trend of the counting rate as a function of the Source-Dosimeter distance before any correction (left panel) after the equalization (centre panel) and after equalization and the correction in z (right panel).

In Fig. 5, we present the effect of the equalization and position-correction procedures on the ratios between the measured radiation, yet to be corrected for the non water equivalence of the scintillator, and the expected TG43-U1 dose [4, 6, 7]. An improvement in the overlap of the curves is clearly visible after each procedure. We can notice deviations from the predicted linearity [4] of these curves due to an insufficient pile-up correction at short distances as well as the stem effect. The first problem can be avoided by shifting the threshold for photon detection to 1.5 photoelectrons and exploiting the optical cross-talk of the SiPMs. As for the stem effect, the issue might be resolved by introducing Cherenkov filters between the sensors and the fibres.

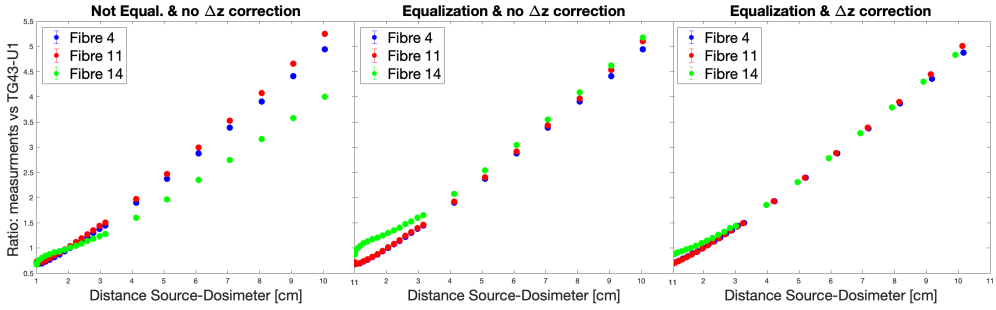

Figure 5: The ratio between the measured dose and the TG43 dose as a function of the Source-Dosimeter distance before any correction (left panel) after the equalization (centre panel) and after equalization and the correction in z (right panel).

4. Conclusion and outlook

Current results confirm the system compliance with the requirements set by the clinical applications. Comparison with the treatment planning system based on the TG43-U1 allows us to turn the pulse counting into a dose measurement. In the single fibre system, at a distance safe from pile-up and stem effect, we proved the ORIGIN system to be TG43-U1 complaint. During the test of the 16-fibres system, we demonstrated the robustness of the designed equalization procedure and obtained precious information on the possible systematics that might endanger the correct functioning of the system. In particular, the accurate positioning of the fibre tips, the pile-up correction and the stem effect result in the main issues and, hence, the focus of our future work. A new measurement

campaign is planned to improve the positioning of the dosimeters along the z-axis. Moreover, we will conduct a series of measurements to select the appropriate filter to curb the stem effect. Finally, analysis of the possibility of raising the photon detection threshold is ongoing. The final qualification will be based on the response in a 3D-printed semi-anatomical phantom developed at the Queen's University of Belfast. The LDR test measurements are ongoing.

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