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ORIGIN, an EU project targeting real-time 3D dose imaging and source localization in brachytherapy: Commissioning and first results of a 16-sensor prototype

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ABSTRACT

The ORIGIN project targets the production and qualification of a real-time radiation dose imaging and source localization system for both Low Dose Rate (LDR) and High Dose Rate (HDR) brachytherapy treatments, namely radiotherapy based on the use of radioactive sources implanted in the patient's body. This goal will be achieved through a 16-fiber sensor system, engineered to house in a clear-fiber tip a small volume of the scintillator to allow point-like measurements of the delivered dose. Each fiber is optically coupled to a sensor with single photon sensitivity (Silicon Photomultipliers — SiPMs) operating in counting mode. The readout is based on the CITIROC1A ASIC by WEEROC, embedded in the FERS-DT5202 scalable platform designed by CAEN S.p.A. Linearity and sensitivity together with the fiber response uniformity, system stability, and measurement reproducibility are key features for a instrument aiming to perform dose measurements. Characterization was carried out in the laboratory, using an X-ray cabinet; preliminary dose rate measurements were performed in clinical conditions.

1. Introduction

The ORIGIN project (optical fiber dose imaging for adaptive brachytherapy)[1] addresses the need to deliver more precise and effective BrachyTherapy (BT) treatments for prostate and gynaecological oncology. Radiotherapy makes use of ionizing radiation for cancer treatment, which is required by 50%–60% of the patients. This treatment can be delivered in the form of external beam radiotherapy, using linear accelerators, or internal radioactive sources (BT). Brachytherapy is further divided into Low Dose Rate (LDR), where the radioactive sources, known as seeds, remain implanted permanently, and High Dose Rate (HDR), where higher activity radiation sources are temporarily implanted. The main characteristics of LDR and HDR-BT are reported in Table 1. The project targets the development of innovative single-point optical fiber dosimeters with inorganic scintillators integrated into the tip. Other systems for in vivo radiation monitoring are currently under development [1–3]. However, they are limited by the number of point-like measurements, not exceeding 4 [1,2], or based on plastic scintillators [3]. Organic scintillators have the main advantage that the measured dose is not affected by energy dependence as for the inorganic scintillators (non-water equivalence of the detector) [4,5]. On the other hand, inorganic scintillators emit light of one or two orders of magnitude larger than plastics [5]. Moreover, the stem effect affects the plastic scintillators' signal when they emit light in the blue (BCF-12) [3].

The ORIGIN system prototype is based on an array of 16 sensors with an acquisition system to provide real-time patient dose imaging by pulse counting, with a spatial resolution of 0.5 mm for HDR and a statistical precision of 5% in 0.1 s and 3 mm and 5% for LDR in 0.5 s over a dose range covering from 1 mGy/s up to 15 Gy/s.

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

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

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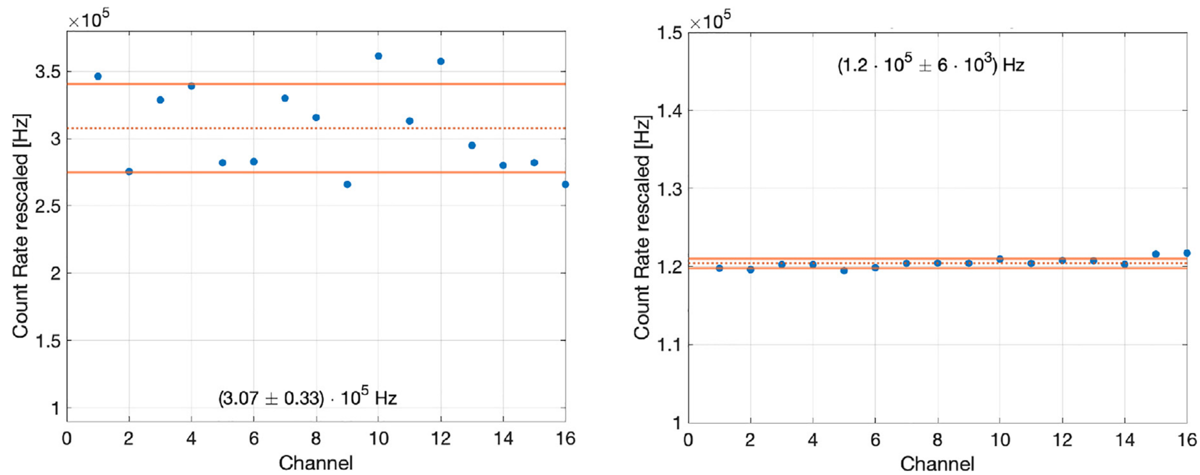

Fig. 1. Left panel: the measured counting rate before the equalization procedure. Right panel: the counting rate after the equalization procedure. The counting rate was measured at a different intensity of the X-ray beam.

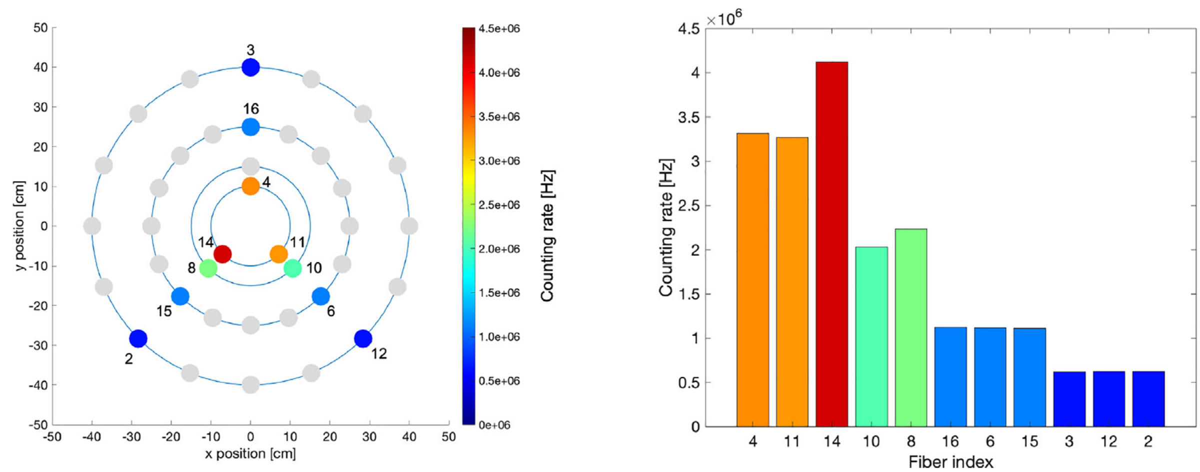

Fig. 2. A quantitative representation when the source is at 0 cm from the dosimeters plane. Left panel the dosimeter plane with the fibers position. Right panel: the measured rate on each fiber.

2. System development

Two sensor types, using different scintillators, were developed: the first one for the LDR-BT based on Gd_2O_2S:Tb (Gadox) and the second one for HDR-BT based on 4 YVO_4:Eu+1 Y_2O_3:Eu (YVO). The selected scintillating materials feature a decay time of about 500 μs and the signal associated with the primary γ ray interaction results in the emission of a trail of single photons [6], opening the possibility to perform dosimetry by pulse counting. The multi-fiber system has been developed using 16 fiber sensors coupled to SiPMs (1 × 1 mm^2 from Ketek[2]), with front-end and readout board based on CAEN FERS (DT5202) board[3] housing the CITIROC1 A [7] a 64 channel front-end ASIC by WEROC enabling triggering a single photon electron level with a maximum counting rate of 20 MHz.

3. Implementation

After successfully verifying that the single-fiber dosimeter system matches the project specifications, we then moved to the 16-channel dosimeter system testing.

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. As expected in HDR-BT, the fiber tips were irradiated with the X-ray beam, providing single photon counting rates up to a few MHz.

Table 1
Main characteristics of LDR and HDR-BT.

	LDR-BT	HDR-BT
Source	^{125}I	^{192}Ir
Implantation	Permanent	Temporary
Activity	∼ 15 MBq	∼ 100 GBq
Half-life	59.41 days	73.83 days
Mean γ-ray energy	27.3 keV	380 keV
λ at Mean γ-ray energy	3 cm	10 cm

The non-uniformity of the fiber response was measured to be 1.2%, dis-homogeneities due to fiber connection and the alignment to the SiPM contributed to 11% variations. Equalization was based on a scaling factor measured by the response of the fibers uniformly irradiated by the X-ray beam. Fig. 1 shows the measured raw counting rate in the left panel and scaled one in the right panel with a residual non-uniformity below 1%.

The clinical evaluation of the system for the HDR-BT was performed at the Queen's University Hospital (Belfast, Ireland). Sensors were positioned in a water equivalent phantom with cylindrical symmetry with an ^{192}Ir source moving along the cylinder axis. The Phantom was immersed in a water tank.

Sensors were positioned at different distances from the phantom axis, along which the source was moved up to 10 cm distance from the sensor plane. An exemplary response for the source position at

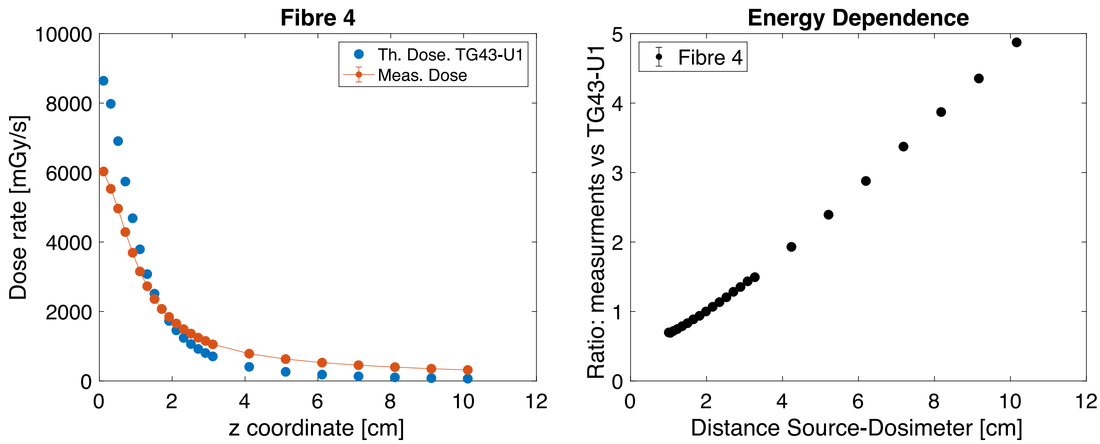

Fig. 3. Left panel: The comparison with the theoretical dose from TG43-U1 with data measured with one of fiber. Right panel: The ratio between the measured dose and TG43-U1 trend. A linear energy dependence was found as in [4].

0 cm distance from the sensor plane is shown in Fig. 2. Data refer to 11 sensors only because 5 were damaged during the assembly. The measurement set allowed us to reconstruct the dose fall-off shown in Fig. 3. Fig. 3 shows the measured dose rate trend compared with the TG43-U1 [8]. The ratio of the TG43-U1 and measured dose provides energy dependence. The linear trend of energy dependence is expected for inorganic scintillators [4,5](see left panel of Fig. 3). The data analysis allows us to estimate a spatial resolution of 0.3 mm at 5 cm and 1.7 mm at 10 cm and statistical precision in 0.1 s of approximately 3% at 10 cm.

4. Outlook

Current results confirm the compliance of the system with the requirements set with the clinical application. Comparison with the treatment planning system is envisaged to turn the pulse counting into a dose measurement and investigate the deviation of the inverse square distance law. The simultaneous response of the 16 fibers provides the base for the reconstruction of the source positioning and relies on a triangulation algorithm. 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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