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Short Communication

In vivo measurement of radiation dose during brachytherapy treatment using scintillation detectors

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Abstract

Introduction: In vivo verification of the delivered dose in brachytherapy remains an unsolved dosimetric problem. Conventional detectors based on ionization chambers, semiconductors or thermoluminescent (TL) materials based on LiF or Al_2O_3:C compounds cannot be used for this purpose. The first way to solve this problem is to use dosimetric materials that can be placed in the patient's body to record the delivered radiation dose *in-situ* using the OSL and/or scintillation phenomena.

Material and Methods: In this work, it was proposed to use a known scintillation crystal of Ce^{3+} doped $Ga_3Ga_3Al_2O_{12}$:Ce garnet (GAGG:Ce) attached with a long optical fiber to measure *in situ* the radiation dose during brachytherapy treatment. The measurements were first performed in a phantom, and then on patients in the clinical conditions of the Oncology Center in Bydgoszcz.

Results: The obtained results are very encouraging. Luminescence spectra from scintillators were recorded using a long optical fiber and a sensitive spectrometer, which can be placed in a safe place. Measurements on the phantom showed the perfect linear correlation between the dose and signal registered by the detector based on the GAGG:Ce crystal. Meanwhile, clinical measurements are subject to some uncertainty regarding the accuracy of detector placement in the treatment planning system and the possible passive emission response of the optical fiber.

Conclusion: Scintillation crystals combined with optical fibers and very sensitive luminescence spectrometers create an ideal measurement system for *in situ* determining the dose of various ionizing radiations. However, their use in clinical practice requires the development of procedures for precisely positioning the detector in relation to the radiation target.

Keywords: brachytherapy; in vivo; scintillation.

Introduction

The prime objective of dose verification in radiotherapy is to test if the delivered dose is carried out in accordance with the treatment plan (TP). Significant discrepancy between direct dose measurements and TP may indicate possible errors in the dose delivered to the patient. Therefore, *in vivo* dosimetry may help dose identify accidents at least at an early stage of the treatment. In vivo measurement in teleradiotherapy is widely used, but measuring dose distribution in brachytherapy poses some difficulties.[1] In brachytherapy the main concern is dose delivery errors resulting from applicator reconstruction errors, and organ or/and applicator movements. Intra-cavitary or intra-tissue measurements are difficult to perform due to problems with the precisions location of the detector. To perform such measurements, the patient's safety must be ensured, e.g. it is not possible to use for this purpose electricity circuits or use toxic substances. Moreover, the measuring detector should be as small as possible and not cause pain or discomfort during the measurement of the dose distribution. The ideal detector should also have no significant distortions in the dose distribution. Detectors with scintillation properties are perfect for such type measurements. Combined with a long optical fiber and a very sensitive spectrometer, such fiber-optic dosimeter (FOD) they make it possible to collect the signal in real time.

Authors' contribution: A – Research concept and design, B – Collection and/or assembly of data, C – Data analysis and interpretation, D – Writing the article, E – Critical revision of the article, F – Final approval of the article.

Material and Methods

Scintillators correspond to the materials that play the role of luminescent transformers of absorbed high-energy ionization radiation in low-energy light in the visible or UV range. Later, the quanta of this low-energy light, proportional to the quantity of high-energy radiation, can be recorded using different photoelectrical devices such as photomultipliers (PMT), photodiodes (PD) or charge-coupled devices (CCD), etc.

Nowadays, a large number of scintillation crystals with excellent properties are available on the market. The crystals of Ce^{3+} doped Gadolinium Aluminium Gallium Garnet ($Gd_3Al_2Ga_3O_{12}$) belong to the class of novel top-scintillators. GAGG:Ce has a density of 6.63 g/cm^3 and Z_{eff} = 54.4, and for this reason, possess a very high absorption coefficient of high-energy rays. The light yield of the GAGG:Ce crystals produced usually by the Czochralski method reach the very high value of 50-60 photon/keV under excitation by γ-quanta. The luminescence band of this scintillator, corresponding to allowed 5d-4f Ce^{3+} transitions, peaked at 530 nm with the decay time of the main emission component in the hundred ns range.[2] Taking into account the mentioned scintillation properties, the GAGG:Ce crystal was selected as a detector material in our research.

The piece of GAGG:Ce crystal with dimension 2×2×0.5 mm was attached to a 4 m optical fiber. Under γ-ray excitation by ^{192}Ir (392 keV) source, the radioluminescence spectra (RL) from the crystal detector were recorded in the 320-1200 nm range using the AvaSpec-HERO spectrometer from Avantes Ltd (Nynomic AG) and collected with chosen readout time interval in the tens-hundred ns range. Before taking measurements in the patient, a series of tests were performed on the phantom with the aim of receiving the calibration curve of the detector in the form of intensity on dose dependence. The modular phantom made of PMMA polymer was printed using a 3D printer. This solution enabled the detector to be irradiated with high precision and repeatability (**Figure 1**).

Results

Measurements in the phantom

TPs were prepared in such a way that our detector was placed in the homogeneous dose area. The series of measurements of the scintillation response of the detector in the dose range from 0.5 Gy to 8 Gy was performed at temperatures close to the temperature of the human body. In this way, the dependences of luminescence spectra intensity vs irradiation dose were obtained and collected in **Figure 2**.

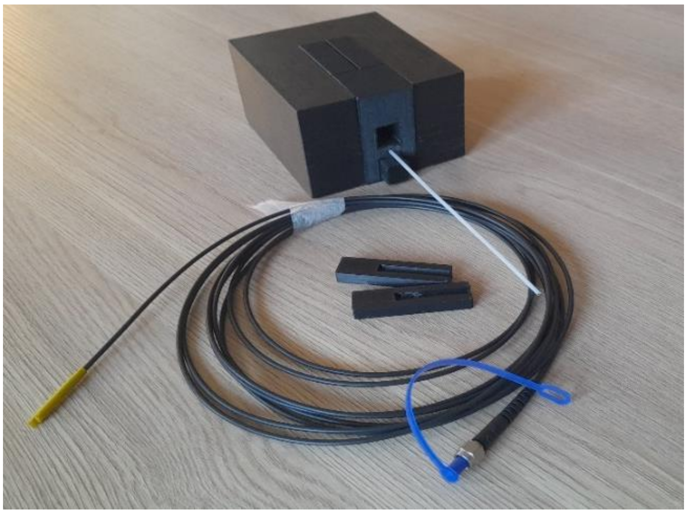

Figure 1. The measurement phantom with the GAAG:Ce crystal scintillator attached to the optical fiber.

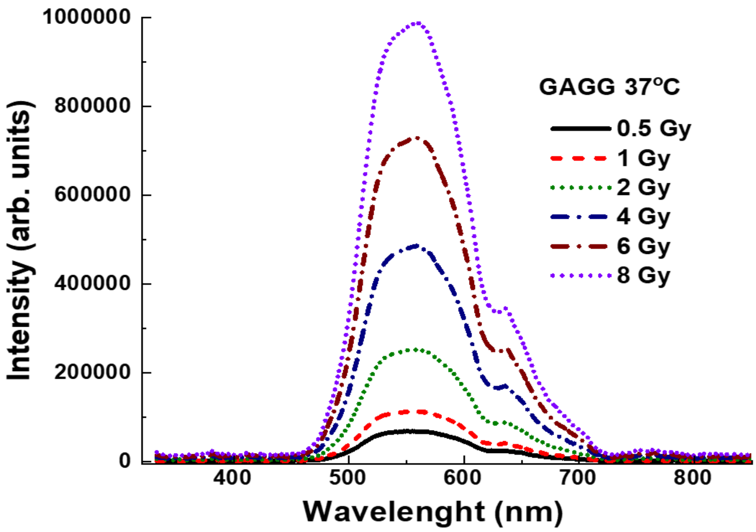

Figure 2. Dependence of intensity of RL spectra of GAAG:Ce crystal detector on radiation dose of γ-rays from ^{192}Ir source in the 0.5-8 Gy range.

RL emission spectra were recorded at different temperatures (room temperature (RT) and patient's body temperature) to check whether increasing the temperature had an effect on the result. Convergent results were obtained. The area under each RL emission spectrum is proportional to the dose absorbed by the detector. In this way, calibration curves *"scintillation response vs dose dependence"* were obtained. Such dependencies are very close to linear (**Figure 3**). Taking into account that the source activity decreases with time and different duration of the treatment procedure, emission spectra were recorded with two readout times of 700 ms and 70 ms. In this way, two calibration curves with matched straight lines were obtained for two different reading modes. Some deviation from the strain line at low (< 0.5 Gy) doses for the calibration curve obtained with a readout time of 700 ms caused by great uncertainty due to the low quantity of light accumulations by the spectrometer at the very short time of irradiation (3-6 s) for this dose range.

Measurements of radiation dose delivery in the patients

Measurements of radiation dose delivery in patients were performed by placing the GAGG:Ce crystal detector in the Foley catheter. Measurements were taken in two patients with uterine tumors. For Patient 1, the detector was placed in the bladder and for Patient 2, in the urethra. The distance of the detector from the radiation source was 37 mm for Patient 1 and 65 mm for Patient 2 (**Figure 4**). Therefore, various signal vs dose responses of detectors were expected due to the significantly different conditions of irradiation.

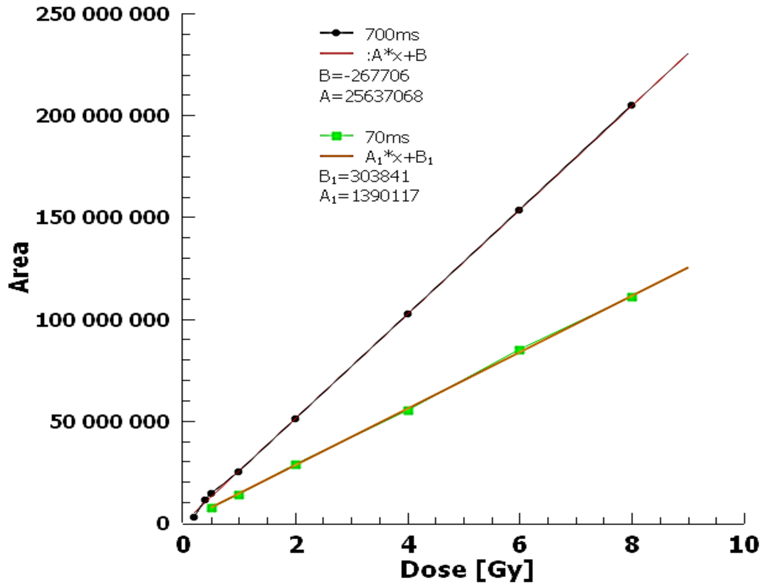

Figure 3. Area under the luminescence curve as a function of the dose of irradiation for two spectrometer readout times modes of 700 ms and 70 ms with matched straight lines.

(a) **(b)**

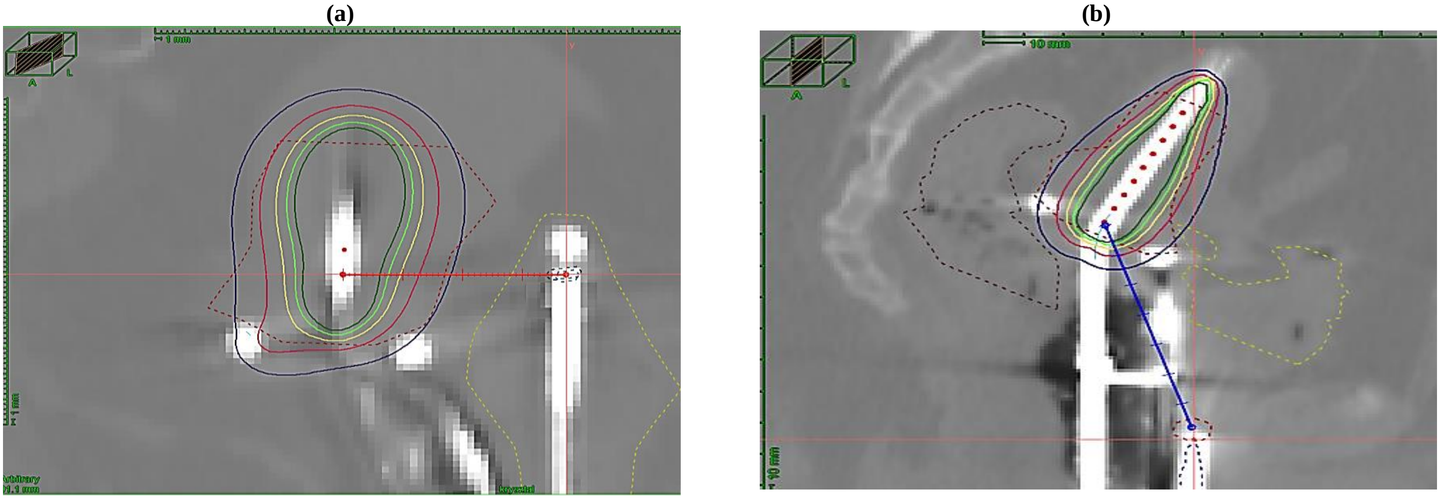

Figure 4. Location of the detector in relation to the radiation source – applicator a) Patient 1 (red line distance 37 mm), b) Patient 2 (blue line distance 65 mm).

Table 1. Summary of calculated doses in the TPS for both patients.

	Patient 1		Patient 2	
	dose [%]	dose [Gy]	dose [%]	dose [Gy]
reconstruction CT	28.4	1.99 ± 0.02	6.2	$0.24 \pm 5\times10^{-5}$
movement	37.3	2.61 ± 0.06	11.3	$0.45 \pm 1\times10^{-4}$
spot dose	33.5	2.34	8.9	0.36

Table 2. Deviations for doses calculated in TPS relative to measurement performed using GAGG:Ce crystal detector.

	Patient 1		Patient 2	
	dose [Gy]	deviation [%]	dose [Gy]	deviation [%]
measured dose	3.19	-	0.42	-
reconstruction CT	1.99	38	0.24	40
movement	2.61	18	0.45	7
spot dose	2.34	27	0.36	14

In brachytherapy**,** the dose distribution is characterized by a large gradient**;** therefore**,** the radiation dose obtained by the crystal during treatment was estimated in three different ways. Firstly, the volume of the crystal is very small (0.002 cm^3), which causes problems in reconstructing the exact position on the computed tomography image. Several possible arrangements were reconstructed**,** and the dose was calculated for them in the treatment planning system (TPS). The next approach was to calculate the dose in TPS taking into account the movement of 2 mm. The point dose, i.e. the isodose passing through the presumed center of the crystal, was also read. The results are presented in **Table 1**.

For the examined patients, the luminescence spectra were measured and collected by the reader and then, using the appropriate calibration curves, the dose absorbed by the crystal was calculated. Namely, for Patient 1 and for Patient 2 the doses were 3.19 Gy and and 0.42 Gy, respectively.

Discussion

The estimated dose in TPS differs notably from the result obtained for the measurement. The largest difference between measurements is for the dose obtained from tomography reconstruction without taking into account the motion shift of the detector. Percentage analysis is given in **Table 2**.

The observed deviations for doses calculated in TPS relative to the measurement may be caused by different phenomena. At first, such deviations can be caused by imprecise positioning of the detector relative to the radiation source. Namely, authors[3] noticed that there is an experimental uncertainty due to random error in the location of the detector with respect to the treatment catheter.[3] As reported in other studies,[4-7] the greatest difficulty is correctly locating the reference/measurement point for crystal detectors. The patient breathes and moves from the moment of CT imaging to the moment of treatment and the direct dose measurements by spectrometer. Therefore, in the case of large dose gradients, even a small change in position can result in a large uncertainty in the dose reading. Meanwhile, using correction on possible mobility of the detector, deviations of results in the 18-7% can be achieved.

The second reason of the observed deviations in dose measurements can be connected with the main drawbacks of measurements with FODs. Namely, in the case of the scintillation detector working with long optical fiber, it is necessary to take into account the so-called *stem effect* connected with additional emission produced by the optical light guide (Cherenkov radiation, phosphorescence and fluorescence of fiber material). It is also necessary to take into account the difference in absorption ability of scintillation crystal and tissue. A detailed analysis of the above-mentioned factors is now under development, and its results will be presented in our group's next publication.

Conclusions

In this work, we have proposed a new fibre-optic dosimeter (FOD) for *in situ* radiation dose measurements during brachytherapy treatment and other medical applications. Such FOD is based on the GAGG:Ce crystal scintillator, long optical fiber and sensitive luminescent spectra reader working with different readout time intervals for collection of the scintillation light. The measurements of radiation dose during brachytherapy treatment were performed first in a phantom, and then for the patients in the clinical conditions of the Oncology Center in Bydgoszcz.

The obtained first results are very engaging and demonstrate the large potential of developed FOD for *in situ* radiation dose measurements. An investigation for the phantom showed the perfect linear correlation between the dose and optical response registered by the scintillation GAGG:Ce crystal detector. Meanwhile, measurements in clinical conditions demonstrated some deviation between the calculated dose using TPS and the real dose measured by FOD. The value of uncertainty between calculated and real dose measurements strongly depends on the value of the radiation dose and the distance between the radiation source and detector.

The last source of uncertainty is the accuracy of detector placement in the patient body in TPS. Namely, the changes in the patient's anatomy cause a shift in the relative position of the detector in comparison with the previous CT image. Consequently, the dose distribution will differ from that predicted.

Measurement for a large gradient in the dose distribution is also subject to localization error. To measure the intra-patient dose, the measurement must be made at a large distance from the radiation source and a correction for mobility must be used.

The second source for uncertainty between calculated and real dose measurements can be caused by *stem effect* connected with using optical fiber for the delivery of light to spectrometer and their contribution to the total light yield of the detector. However, the obtained large repeatability of phantom measurements during calibration curve preparation allows strongly decreasing stem effect influence and gives hope that the developed FOD on the base of GAGG:Ce scintillation crystal will be able to be used to control the dose in any radiotherapy applications.

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Editor's comment

The abstract of the work was submitted to the 18th Congress of the Polish Society of Medical Physics (held in Poznań, Poland, 19-21 September 2024). The authors of the work were invited by the Scientific Committee of the Congress and the Editor-in-Chief of the Polish Journal of Medical Physics and Engineering to present their work in the form of a Short Communication in the Journal.

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