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3D dose distribution measurements in brachytherapy using radiochromic gel dosimeters

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ABSTRACT

The paper informs about the joint research project "Increasing cancer treatment efficacy using 3D brachytherapy" which is a three-year project carried out in cooperation with European national metrology institutes and co-funded by the European Community's Seventh Framework Program for research and technological development. The goal of the project is to improve the measurement and standardization of dose-to-water rate by brachytherapy (BT) sources. The paper gives a summary of the individual parts of the whole project and describes in more detail the task of the Czech Metrology Institute: the determination of spatial distribution of dose-to-water by BT sources using radiochromic gel dosimeters, including a new gel with suppressed diffusion. The response of irradiated gels is evaluated using the optical cone beam computed tomography (CT) technique. The characteristics of the optical CT scanner are discussed with respect to CCD camera performance and light source. The optimized composition of the new gel and its dosimetric properties are highlighted. The results show that the radiochromic gels are convenient for measuring the 3D distribution of dose-to-water and could be an alternative to current methods of dose distribution measurements.

1. Introduction

Brachytherapy (BT) is a therapeutic method based on killing tumor cells by ionizing radiation at short distance, i.e. small encapsulated radioactive sources are placed directly into a tumor delivering a high dose to the tumor while sparing the surrounding healthy tissue. It is an important use of ionizing radiation in medicine. However, the metrology of BT sources has fallen behind and has not advanced in line with BT treatment procedures. This causes greater uncertainties in delivered doses which can lead to the under- or over-irradiation of a targeted tumor. Furthermore, the irradiation procedure is not optimized. For this reason many national medical associations and scientific international organizations have begun to increase their efforts to improve and disseminate the metrology of BT sources. This paper describes a project researched within the scope of the European Metrology Research Project (EMRP) organized by EURAMET.

2. Description of the project

The joint research project "Increasing cancer treatment efficacy using 3D brachytherapy" is a three-year project which commenced in 2008 and is co-funded by the European Community's Seventh Framework Program for research and technological development, within the framework of the ERA-NET Plus activities, under the iMERA-Plus Project (implementing Metrology in the European Research Area). The project is carried out in close cooperation with European national metrology institutes and refers to research in ionizing radiation metrology within the framework of the targeted program "Health" of the EMRP [1]. Its main goal is to improve the measurement and standardization of dose-to-water rate by BT sources. The main tasks of the project are [1,2]:

- developing and commissioning a system of primary standards for the measurement of the absorbed dose-to-water (aim for an uncertainty $u(D_W) \leq 2\%$, $k=1$) by low-dose-rate (LDR) BT sources, at the reference distance of 1 cm from the source [3];
- developing and commissioning a system of primary standards for the measurement of the absorbed dose-to-water (aim for an uncertainty $u(D_W) \leq 2\%$, $k=1$) by high-dose-rate (HDR) BT sources, at the reference distance of 1 cm from the source [3];
- establishment of an absorbed dose-to-water based metrology chain for LDR and HDR BT sources, to assure traceability in absorbed dose measurements in secondary standard laboratories and medical centers;
- establishment of a procedure to verify the relative 3D distribution of the absorbed dose-to-water rate by BT sources in a water or water-equivalent phantom with an uncertainty of

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less than 5% (k=1) at clinically relevant distances, to standardize the measurements in medical centers.

The major European national metrology institutes in the field of ionizing radiation measurements are participating in the project: BEV (Austria), CMI (Czech Republic), ENEA-INMRI (Italy; project coordinator), ITN-LMRI (Portugal), LNE-LNHB (France), NMI-VSL (The Netherlands), NPL (United Kingdom), PTB (Germany), SSM (Sweden), and STUK (Finland). The Czech Metrology Institute (CMI) is focused on the measurement of relative 3D dose distributions using radiochromic gel dosimeters. The tasks to be solved are: as measurement of (a) the dose response and (b) energy response of the gels, (c) construction of a water phantom, (d) characterization of the optical scanner performance using a dummy phantom, (e) measurement of relative 3D dose distributions, and (f) Monte Carlo calculations of 3D dose distributions around selected BT sources. The following text briefly presents some of the results obtained so far.

3. Materials and methods

3.1. Gel dosimeters

The CMI exploited two types of gels for the measurement of 3D dose distributions: a Fricke-infused gelatin gel with xylenol orange Fe^{3+} ion indicator (the FXG dosimeter) [4] and an agarose gel based on the radiation-induced creation of Turnbull blue dye (the TBG dosimeter). The composition of both gels and the characteristics of the latter one are described in Ref. [5]. Due to the fast feathering of dose patterns in the FXG dosimeter, it is supposed to mainly use the TBG dosimeter which does not suffer from diffusion. The improved chemical composition and preparation procedure of the TBG dosimeter has recently been found.

The improved TBG dosimeter consists of de-ionized water, phytagel (0.4% w/w; a gelling agent similar to agarose), potassium ferricyanide (3 mM), and ferric chloride (0.75 mM). The preparation procedure was the same as described in Ref. [5] with exception to the following: (a) neither ferric ammonium citrate nor hydrochloric acid were used, (b) the water solution of ferric chloride was heated to 60 °C until the solution colored with the creation of ferric hydroxide, and (c) the temperature of the phytagel and the ferric hydroxide solution at the final point of mixing of the gel were ~35 and ~40 °C, respectively. The fabricated gel was poured (a) into one 800 ml home-made cylindrical vessel (9 cm in diameter) with 0.5 mm thick teflon wall and (b) into plastic spectrophotometric cuvettes with inner dimensions $1 \times 1 \times 4.5\,cm^3$ (Brand GMBH, Germany), and refrigerated. The gel in the vessel solidified after approximately 3 h. The gel was subsequently irradiated with two crossed external photon beams from the ^{60}Co irradiator Chisobalt 2 B75 to test the performance of the improved gel. The beams had a $1.5 \times 2.0\,cm^2$ rectangular profile which entered the vessel at approximately 45° angle. The dose at the spot where each beam entered the gel reached 70 Gy (the dose rate was 90 Gy/h). The gel response was then evaluated using the optical computed tomography (CT) scanner. The gel samples in the cuvettes were irradiated with ^{60}Co photon beam with doses between 2 and 140 Gy. The following day the spectrophotometric absorbance of samples was measured at a wavelength of 690 nm (Helios β, Thermo Scientific).

3.2. Optical computed tomography scanner

The optical CT is an ideal method for the evaluation of gel response because the dose distribution delivered to the gel is represented by a change in color of the gel. A home-made optical CT scanner was used for the reconstruction of optical density images recorded inside the gel. It is composed of the following main parts: (a) a 16-bit astronomy charged-coupled device (CCD) camera (G2-0402 type, Moravian Instruments, Czech Republic) with a set of color filters, (b) a water bath, (c) a stepper motor synchronized with the CCD camera and connected to a rotating table inside the water bath, and (d) a light source, either a planar diffuse white-light source or a red diode (L-53SRC-F type, Kingbright) array emitting light at a peak wavelength of 660 nm (suitable for the evaluation of the TBG dosimeter response).

Several measurements were performed to test the optical performance of the optical CT scanner. The first measurement determined the response function of the CCD camera. A transparent object was photographed with a wide range of exposure times and several different f-numbers to find a relation

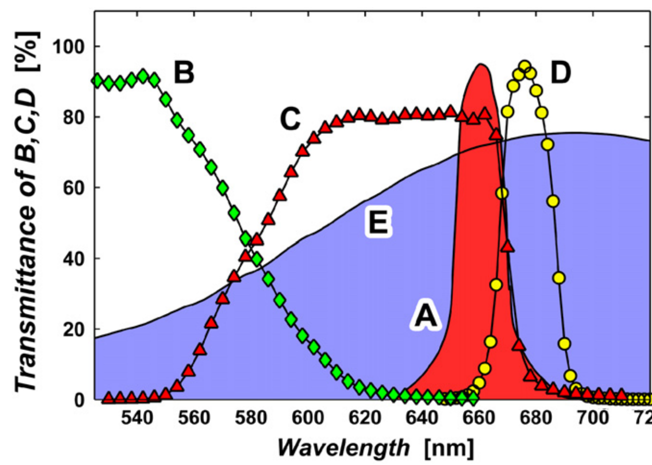

Fig. 1. Intervals of light transmittance of green (curve B), red (C), and SII (D) color filters in comparison to the emission spectrum of red diodes ((A) manufacturer data, relative values, diode type L-53SRC-F, Kingbright) and to the absorption spectrum of Turnbull blue dye ((E) relative values). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

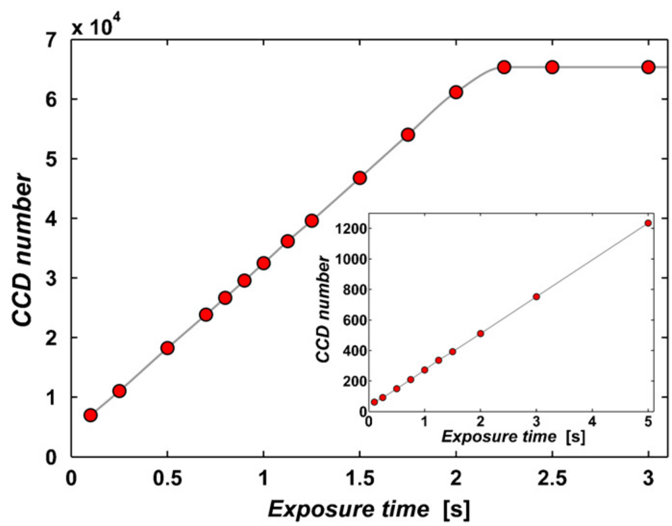

Fig. 2. Response of the CCD chip to the light flux. The dependence is linear over the whole dynamic range of the CCD chip—from very low pixel intensities corresponding to the CCD chip noise (pixel intensities ~50) and up to the chip saturation at the pixel intensity 2^{16} (65536). This means that even very dark photographs can be used for the reconstruction of optical density images without the necessity for any non-linear calibration. The embedded figure shows the detail of low pixel intensities. Slopes of both lines are different due to different light conditions used because the minimum camera exposure time is 0.15 s.