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Time-resolved *in vivo* dosimetry for source tracking in brachytherapy

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ABSTRACT

PURPOSE: The purpose of this article is to demonstrate that brachytherapy source tracking can be realized with *in vivo* dosimetry. This concept could enable real-time treatment monitoring.

METHODS: *In vivo* dosimetry was incorporated in the clinical routine during high-dose-rate prostate brachytherapy at Aarhus University Hospital. The dosimetry was performed with a radioluminescent crystal positioned in a dedicated brachytherapy needle in the prostate. The dose rate was recorded every 50−100 ms during treatment and analyzed retrospectively. The measured total delivered dose and dose rates for each dwell position with dwell times >0.7 s were compared with expected values. Furthermore, the distance between the source and dosimeter, which was derived from the measured dose rates, was compared with expected values. The measured dose rate pattern in each needle was used to determine the most likely position of the needle relative to the dosimeter.

RESULTS: In total, 305 needles and 3239 dwell positions were analyzed based on 20 treatments. The measured total doses differed from the expected values by −4.7 ± 8.4% (1SD) with range (−17% to 12%). It was possible to determine needle shifts for 304 out of 305 needles. The mean radial needle shift between imaging and treatment was 0.2 ± 1.1 mm (1SD), and the mean longitudinal shift was 0.3 ± 2.0 mm (1SD).

CONCLUSION: Time-resolved *in vivo* dosimetry can be used to provide geometric information about the treatment progression of afterloading brachytherapy. This information may provide a clear indication of errors and uncertainties during a treatment and, therefore, enables real-time treatment monitoring.

Keywords: *In vivo* dosimetry; HDR brachytherapy; Source tracking; Dose rate measurement; Prostate cancer

Introduction

Brachytherapy is a radiotherapy modality which involves a considerable number of manual procedures during treatment planning and delivery. Several investigations of radiation misadministrations in brachytherapy have shown that a substantial share of the events is caused by human errors (1−3). The identified misadministrations involved a large range of different events including wrong connections of transfer tubes, reconstruction errors, and wrongly assigned source strength. Many events may remain unnoticed, and if detected, they are typically only identified posttreatment, due to the limited availability of commercial real-time treatment-monitoring systems. Furthermore, commercial software tools and algorithms that can provide guidance in the event of a treatment error are not available (4, 5).

The development of treatment monitoring in brachytherapy has mainly focused on three approaches: imaging, tracking, and *in vivo* dosimetry (6). Imaging has the advantage of providing a direct link between source/applicator geometry and patient anatomy. However, extra acquisition and analysis of 3D imaging adds additional time to the treatment procedure. Furthermore, 3D imaging is typically not completely real-time, except for advanced

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setups as for example, suites including both afterloading units and MRI (7). Fluoroscopy provides real-time information but does not include soft tissue information, and the quality of the flouroscopy images is challenged by the radiation from the treatment source, at least during high-dose-rate (HDR) treatments (8, 9). This challenge has been overcome by increasing the X-ray strength and reducing the monitoring frequency (10). Electromagnetic tracking provides high geometric accuracy but is limited by the fact that the source is not tracked directly and that it does not link the geometric verification to the patient anatomy (11−14). *In vivo* dosimetry facilitates direct measurement of the absorbed dose in organs at risk (OAR) or close to the tumor. However, *in vivo* dosimetry is challenged by large positioning uncertainties of the dosimeters, limited utilization of real-time readouts, and that each dosimeter only provides the dose at a given point. Certain dosimeter types can only measure the accumulated dose (e.g., thermoluminescence dosimeter and alanine) while others can measure dose rates (e.g., diodes, metal-oxid-semiconductor field effect transistor and scintillators) (4, 5, 15, 16). Recent developments have reduced the size of detectors and the positional uncertainty and increased the sensitivity (agreement within 5%) and read-out frequency (>10 Hz) (17−23).

This article will present *in vivo* dosimetry measurements performed with a system featuring high read out frequency, facilitating a study of individual dwell positions. The ability to analyze the dose rates for each dwell position opens new ways of identifying errors and uncertainties. Kertzscher *et al.* developed an adaptive algorithm for treatment monitoring, in which the most likely dosimeter position was determined (24). This article applies a methodology where dose rate for each dwell position is used to determine the positions of the individual treatment needles relative to the dosimeter. Source tracking with multipoint dosimeter has previously been explored both in phantoms (25−29) and in pulsed dose rate cervix treatments (30), but this is the first time a single dosimeter has been used for obtaining geometrical information for each individual needle in a considerable number of patients. The ability to track the source directly enables identification of misplacements of the source relative to the dosimeter. Detectable misplacements could be, for example, needle reconstruction errors, wrong connections of guide tubes or positional offsets by the afterloader, whereas an identical shift of both source and dosimeter relative to the anatomy cannot be detected.

Methods and materials

The instruments and dose measurements

The *in vivo* dosimetry was performed using a small (0.5 × 0.5 × 2 mm^3) radioluminescent crystal made of Al_2O_3:C grown by Landauer Inc (USA) using the Czochralski technique (growth CZ#60). The crystal was coupled to a 15 m long optical fiber connecting to a data acquisition box (DAQ). The DAQ consisted of a bandpass filter (395−440 nm), a photo multiplier tube (PMT) (Hamamatsu h7360-01), and a DAQ card (NI9402). The bandpass filter was placed between the PMT and the optical fiber to accept the peak wavelength region of the Al_2O_3:C emission and remove the other wavelengths of the contaminating Cerenkov and fluorescence light that is emitted in the optical fiber, referred to as the stem effect (19, 31, 32). The PMT was connected to the DAQ card, which counted the number of detected photons in a given time interval. The crystal and optical fiber were shielded from light using a plastic tube. The outer diameter of the crystal and tube was 1 mm, which was thin enough to fit into the brachytherapy plastic needles used for the treatment. The DAQ was placed in a neighboring radiation shielded room to avoid false signals from radiation striking the PMT. The entire system is described in details in the study by Andersen *et al.* (19), which also contains a schematic drawing of the system and a detailed characterization of the crystal.

The clinical procedure

The *in vivo* dosimetry procedure was carried out by the clinical staff as an integrated part of the clinical brachytherapy procedure. Patients with D'Amico high-risk prostate cancer were treated with a combination of external beam radiotherapy (46 Gy in 23 fractions) and two individual fractions of HDR brachytherapy of each 8.5 Gy prescribed to the prostate + 3 mm (33). Before implantation of needles in the patient, pre-irradiation and calibration of the crystal were performed by the medical physicist to account for potential changes in the detection efficiency of the system, for instance due to a recoupling of the optical fiber to the DAQ-box. This process was performed using a block of solid water with two parallel needles separated by 10.4 ± 0.2 mm and took 15−30 minutes depending on the source strength (34). Transperineal insertion of plastic needles was performed under live transrectal ultrasound guidance. After insertion of all treatment needles, an additional needle, dedicated to the dosimeter, was positioned in the prostate as best feasible but preferentially in the center of the gland. Approximately, 1 h after needle implantation, the patient underwent an axial T2W MRIs acquired with a 2-mm slice thickness and a 1.4-mm transversal accuracy. The MRI was used for treatment planning, which involved contouring, needle reconstruction, dosimeter localization, and dose optimization (Oncentra Prostate 4.2.21, Elekta). Immediately before treatment delivery, an additional MR scan was obtained to detect and adjust for needle migration >3 mm, followed by reoptimization of the plan. Immediately before dose delivery, the dosimeter was placed in the dedicated needle and inserted to the end of the lumen, with the center of the luminescent crystal located 9.5 mm from the outer tip of the needle, based on X-ray exposure