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Dosimetry modeling for focal high-dose-rate prostate brachytherapy

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ABSTRACT

PURPOSE: The dosimetry of focal high-dose-rate prostate brachytherapy was assessed. Dose volume histogram parameters, robustness to source position errors, and Monte Carlo (MC) simulations were compared for whole-gland (WG), hemi-gland (HEMI), and ultra-focal (UF) treatment plans.
METHODS AND MATERIALS: Tumor volumes were delineated based on MRI and template biopsy results for 9 patients. WG, HEMI, and UF plans were produced assuming 19 Gy single fraction monotherapy treatments. For UF plans, a 6-mm margin was applied to the visible tumor to create a focal-planning target volume (F-PTV). Systematic source position shifts of 1–4 mm were applied to assess plan robustness. The dosimetric impact of steel catheters was assessed using MC simulation.
RESULTS: Mean D_{90} and V_{100} were 20.4 Gy and 97.9% for prostate in WG plans, 22.2 Gy and 98.1% for hemi-prostate in HEMI plans, and 23.0 Gy and 98.2% for F-PTV in UF plans. Mean urethra D_{10} was 20.3, 19.7, and 9.2 Gy in WG, HEMI, and UF plans, respectively. Mean rectal D_{2cc} was 12.5, 9.8, and 4.6 Gy in WG, HEMI, and UF plans, respectively. Focal treatment plans were sensitive to source position errors—2 mm systematic shifts reduced mean prostate D_{90} by 0.7%, hemi-prostate D_{90} by 2.6%, and F-PTV D_{90} by 8.3% in WG, HEMI, and UF plans, respectively. MC simulation results were similar for all plan types with most dose volume histogram parameters reduced by <2%.
CONCLUSIONS: HEMI and UF treatments can achieve higher D_{90} values compared with WG treatments with reduced organ at risk dose. Focal treatments are more sensitive to systematic source position errors than WG treatments.

Keywords: Prostate brachytherapy; Focal therapy; High-dose-rate brachytherapy

Introduction

Brachytherapy is a well-established treatment modality for prostate cancer. Treatments routinely target the whole prostate gland, are either low-dose-rate (LDR) or high-dose-rate (HDR) and may be given as stand-alone treatments or in combination with external beam therapy (1, 2). Prostate brachytherapy patients may suffer some side effects in terms of urethral, rectal, and sexual function (1, 3). In focal prostate brachytherapy, the aim is to reduce dose to the organs at risk by targeting treatment to areas of the prostate known to contain tumor, with reduced dose to the prostate gland as a whole (3). The objective is to achieve equivalent rates of tumor control as whole-gland (WG) treatment while reducing treatment related toxicities. There are few articles in the literature describing focal therapy treatment planning. Cossett *et al.* (4) describe a pilot study treating focal tumor volumes for 21 patients with an LDR technique. Kamrava *et al.* (5) completed a retrospective planning study for 10 patients comparing WG and hemi-gland (HEMI) treatments for HDR. Todor *et al.* (6) describe a planning study for a focused LDR treatment using mixed isotopes to achieve two different dose levels, with a focal tumor volume receiving the higher dose level and the whole prostate treated to a reduced level. Nguyen *et al.* (7) describe a focal treatment targeting the peripheral zone of the prostate. In addition, several groups have investigated or implemented HDR focal boost treatments where the whole prostate is

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treated, but the focal tumor volume is boosted to a higher dose level (8–13)—an approach intended to improve tumor control rates while keeping toxicities at a similar level.

This study investigates three aspects of treatment planning for HDR focal prostate brachytherapy. Firstly, it compares target and organ at risk doses for different treatment planning approaches: whole prostate, HEMI, and ultra-focal (UF) treatments. Secondly, plan robustness is assessed to determine whether focal treatments are more sensitive to source position errors than standard treatments. Finally, Monte Carlo (MC) simulation of the treatment plans is performed to assess whether focal therapy plans are more sensitive than standard plans to dosimetric errors introduced by differences between AAPM Task Group No. 43 Report (14) and advanced dose calculation methods, for example, because of attenuation of dose due to delivering treatment through steel catheters.

Methods and materials

Patient selection and tumor delineation

Treatment planning for this dosimetric modeling study was based on MRI data from a group at University College London Hospital performing clinical trials of focal therapy using high-intensity focused ultrasound (15), for 14 patients who were considered candidates for focal therapy according to the patient characteristics defined by a recent consensus report (3) for LDR focal therapy. Patients were aged 52–77 years and had low- or intermediate-risk disease. Patients were evaluated based on clinical data, T2-weighted MRI and diffusion-weighted MRI, and template mapping biopsy data. MRI data were acquired on an Avanto (Siemens AG, Munich, Germany) 1.5 T scanner using phased-array pelvic and spine coils for signal reception. T2-weighted MRI used a turbo-spin echo sequence with slice thickness 3 mm and 0.7-mm pixel size. Diffusion-weighted MRI used a single shot spin-echo echo planar imaging sequence with slice thickness 5 mm, 1.5-mm pixel size, and b-values 0, 150, 500, and 1000 s/mm^2. The MRI volumes were rotated so that the position of the prostate approximated that used in transrectal ultrasound (TRUS)–based treatment planning (flat posterior prostate capsule), as is practiced in our center. A consultant radiologist with 18 years experience of prostate MRI delineated focal-gross tumor volumes (F-GTVs). F-GTVs were delineated where suspicious regions in the MRI data agreed with tumor locations from template biopsy data. The prostate, urethra, rectum, and bladder were delineated based on the T2-weighted MRI.

Treatment planning

The treatment planning system (TPS) used was Oncentra Prostate v4.0 (Elekta AB, Stockholm, Sweden). Three treatment plans were created for each patient: a standard WG treatment, a HEMI treatment treating the half of the prostate containing the tumor volume, and a UF treatment treating the tumor volume plus a margin. These target definitions were taken from an LDR focal therapy consensus report (3). For WG plans, a 3-mm margin was applied to the prostate (0 mm posteriorly) to create a planning target volume (PTV) (1). For HEMI plans, the same margin was applied to the hemi-prostate, excluding the urethra, to create a hemi-PTV (H-PTV). For UF plans, a 6-mm margin was applied to the F-GTV to create a focal-PTV (F-PTV). The F-PTV was constrained to avoid the urethra and to remain within the PTV defined for WG plans. All treatment plans assumed a single fraction monotherapy treatment with 19 Gy prescribed to the prostate/hemi-prostate/F-PTV. This dose prescription has been used for single fraction WG treatments in recent studies (16, 17) and has been shown by modeling studies to be a suitable dose for single fraction treatments (18). For WG plans, virtual catheters were placed using our standard clinical approach; approximately 1 cm apart around the periphery of the target as visualized at midgland, with 2–5 additional catheters (depending on the size of the prostate) to cover the central regions, prostate apex, and prostate base. For HEMI plans, catheter placing was similar with additional catheters near the urethra to try and cover the hemi-gland without increasing urethral dose. For UF plans, catheter density was increased on the assumption that this would improve dose conformality for a small target. Catheters were spaced approximately 0.75 cm apart across the full mediolateral and anteroposterior extent of the F-PTV as visualized on multiple transverse slices. The 0.75-cm spacing was achieved by placing catheters alternately 0.5 or 1 cm apart in the template grid and tracking the catheters to the desired position. This tracking is clinically realistic as we routinely steer catheters in this manner during clinical implants. Dose volume histogram (DVH)–based inverse optimization (19) was used to generate the treatment plan, with small manual adjustments to dwell times if necessary. Dose was calculated on a $1 \times 1 \times 1$ mm^3 grid over the entire imaging volume and the DVH calculation used 50,000 points with 0.95 Gy dose bins. Dose constraints for organs at risk were the same for all plans: urethra $D_{10} < 22$ Gy, $D_{30} < 20.8$ Gy, and rectum $D_{2cc} < 15$ Gy, $V_{100} = 0\%$ (16). Planning objectives were to aim for 100% prescription dose coverage of the prostate in WG plans, hemi-prostate in HEMI plans, and F-PTV in UF plans.

Plan robustness

Robustness analysis was performed for each plan by applying systematic shifts across all source positions. Shifts of 1–4 mm were applied separately in each anatomic direction. Random source position errors were not investigated as it was felt that for HDR prostate brachytherapy, random errors are likely to be small compared with systematic errors. Source positions, dwell times, and structure sets were exported from the TPS. DVH parameters were recalculated for each plan after applying the shift to all source positions, using dose and DVH calculation code implemented in MATLAB