MRI-Guided HDR Brachytherapy for Prostate Cancer

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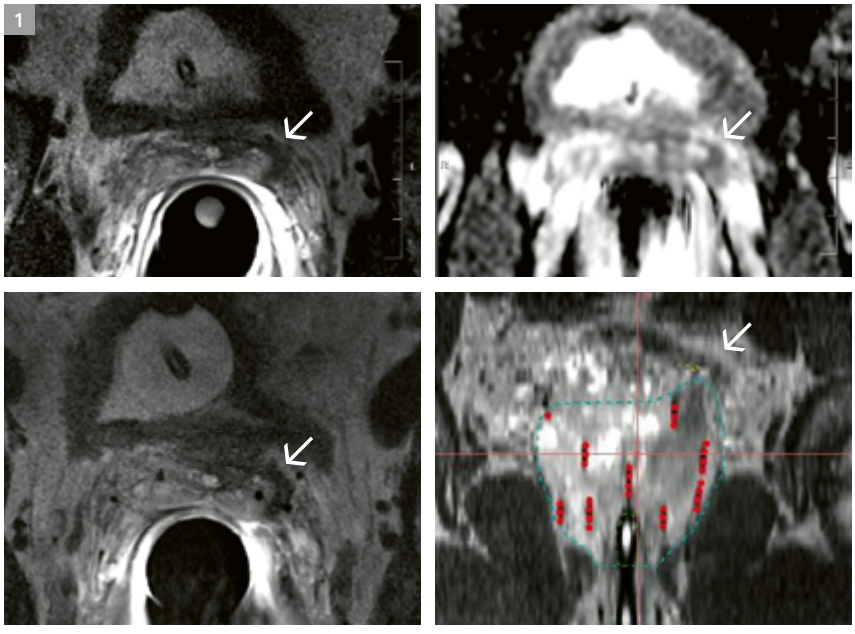
Introduction

Prostate brachytherapy, either as monotherapy or as a boost to external beam radiotherapy, can achieve unparalleled dose escalation, with doses (EQD2) upwards of 150 Gy when the dose gradient is taken into account [1]. As evidence mounts supporting the value of dose-escalation [2, 3], so has the adoption of high-dose-rate brachytherapy in clinical practice across the world.

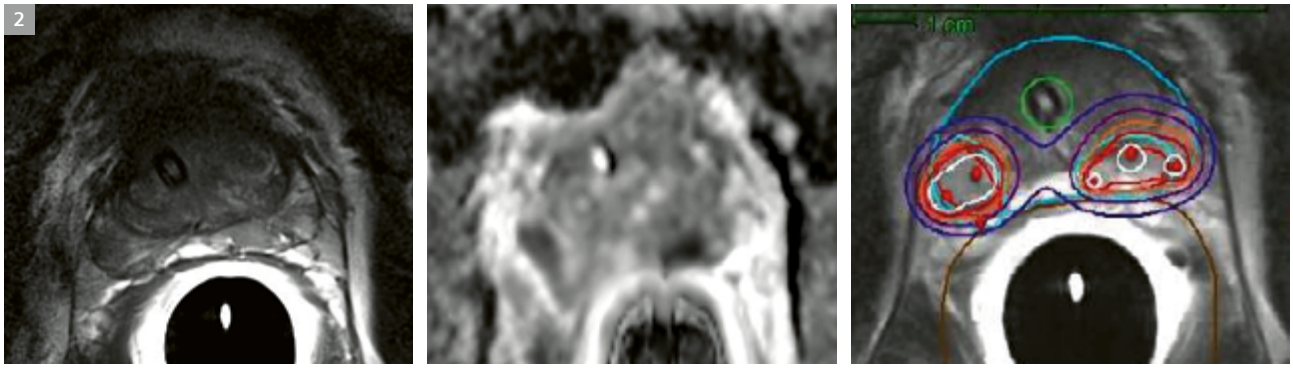
Although trans-rectal ultrasound (TRUS) remains the standard-care interventional imaging modality for guidance of prostate brachytherapy, it falters in its depiction of implanted devices, such as brachytherapy needles, and/or catheters due to substantial echogenic artifact that degrades image quality as the implant progresses. It also fails in depicting regions of tumor burden that should be considered in the implant and treatment.

MRI is considered state-of-the-art for local tumor staging and visualization. A diagnostic acquisition protocol that includes high-resolution T2-weighted FSE and diffusion-weighted imaging (DWI) with or without dynamic imaging during IV contrast injection, can accurately identify regions of gross tumor burden (GTV) and the presence of gross extracapsular extension or seminal vesicle invasion (stage T3) [4].

The prostate gland is a flawed surrogate target for cancer as a target for brachytherapy, as cancer is neither defined nor confined to the boundaries of the prostate gland. The gross target volume (GTV) should be considered in planning and executing brachytherapy for prostate cancer, and in this regard, MRI prior to implantation is paramount. The introduction of MRI to augment or replace the TRUS workflow has logically progressed over the past decades. Here we present our current state-of-the-art approach to interventional MRI applied to HDR brachytherapy for prostate cancer.



1 Patient with left seminal vesicle invasion (arrow). Catheters (signal void) are implanted deep and adjacent to extraprostatic disease (bottom), which can then be included in the target volume (turquoise) for HDR. brachytherapy.



2 Patient with intermediate-risk prostate cancer and two gross target volumes in the right lateral peripheral zone, and left medial peripheral zone. Both targets are implanted for a boost to external bean radiotherapy in order to improve tumor control (isodose plan, right).

Why MRI after catheter placement?

Dose plans in HDR brachytherapy are generated after catheter insertion in order to prescribe the time that the radioactive source spends at each pre-defined 'dwell' position. Dwell-time optimization is a powerful variable after catheter placement by which dose is focused on targets at risk while reducing exposures to nearby organs and structures at risk of injury, such as the rectum. By replacing standard TRUS or CT with MRI for treatment planning, depiction of anatomic boundaries relative to implanted catheters is vastly improved [5].

In the absence of commercial MRI markers, catheter signatures can be accentuated as signal voids in a high-resolution FSE image using an intermediate echo-time (TE) (Fig. 1), or by using a dual-echo FSE acquisition in order to acquire a proton-density-weighted (PD) image for device reconstruction, and a matched T2-weighted FSE image for anatomic delineation. Although this approach presents an improvement in accuracy of delineating the prostate gland, blurring of the apical boundary can occur due to acute needle trauma and bleeding. Depiction of gross tumor is also degraded by edema and bleeding compared with MRI prior to catheter insertion.

Why MRI before catheter placement?

MRI acquired prior to brachytherapy is most critical, whereby the appropriateness of the treatment is confirmed, and images cognitively 'fused' or considered during the implant to avoid marginal miss of gross tumor. This approach results in a change in treatment plan in a substantial proportion of patients, either through the addition of hormonal therapy, the addition of external beam radiotherapy, and/or modification of the implant itself by including sites of extraprostatic extension and/or seminal vesicle invasion [6] (Fig. 1). Sites of tumor burden can also be considered when trading off target coverage and dose to adjacent organs at risk, such that undercoverage is permitted only in regions that do not harbor gross tumor.

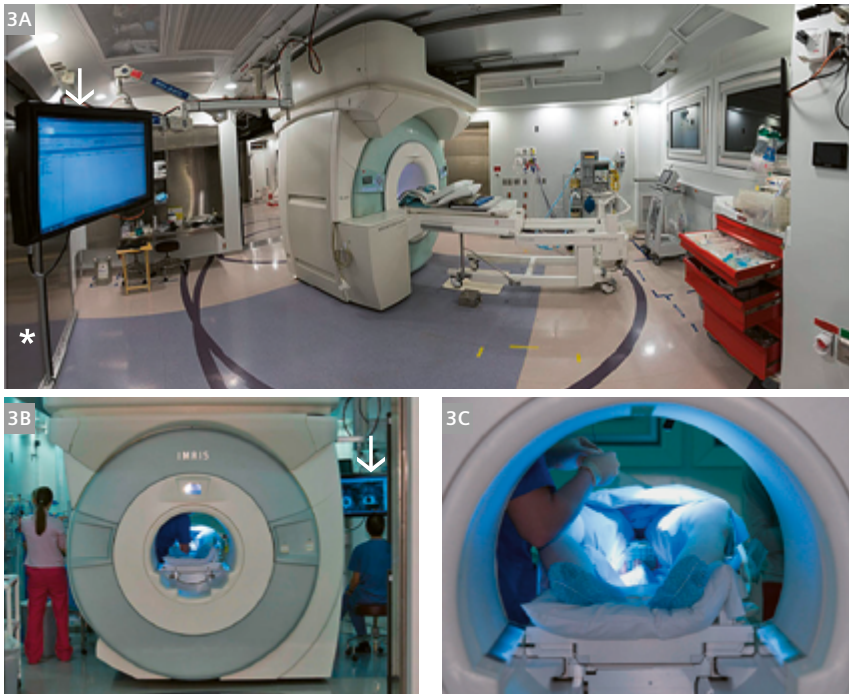
The next step is to differentially dose escalate visible tumor, and potentially de-escalate dose to microscopically involved prostate gland tissues distant to the GTV. A number of publications, predominantly in HDR applications, have demonstrated ease of escalating dose to tumors without incurring elevated dose to organs-at-risk (OARs) [7]. We await results of prospective trials to better ascertain the relative gain in effectiveness with this approach. It remains that the success or failure of tumor boost and/or focal-only therapies hinge on highly accurate techniques (Fig. 2). Sources of error and uncertainty introduced with MRI-TRUS registration remain to be addressed.

Why an MRI-only prostate brachytherapy workflow?

An MRI-only workflow permits MRI to be acquired prior to and during catheter insertion to aid in implant guidance, and after catheter insertion for MRI-based treatment planning. In this manner, registration errors are largely circumvented. The requirement for a separate visit for a diagnostic MRI prior to brachytherapy is also removed. We demonstrate our installation that integrates an MRI scanner (1.5T MAGNETOM Espree, Siemens Healthcare) with the HDR delivery (Elekta MicroSelectron HDR) suite, removing the need for patient transfer between treatment-planning MRI and delivery of HDR brachytherapy dose [8] (Fig. 3). Errors due to motion or swelling are thereby further mitigated, and imaging immediately after (or during) delivery can confirm delivered (in contrast to planned) dose.

The Interventional MRI procedure

Patients are placed in frog-leg on a patient positioning system atop the diagnostic table. An endorectal coil (Sentinelle Endocoil Array, Siemens Healthcare) is secured and fixed perpendicular to a custom perineal template. The perineum is prepped and draped with patients under general anesthesia (continuous infusion propofol).



3 MRgBT suite at the Princess Margaret in Toronto. A 1.5T MRI scanner on rails is brought into the brachytherapy suite. Equipment that is not MRI safe (including HDR afterloader) is stored behind RF doors **(3A, see ✱)**. Brachytherapy catheters are inserted stereotactically with patient in frog-leg fashion using a positioning system and endorectal coil (Sentinel Endocoil Array), and a custom perineal template. In-room navigation display **(3A and 3B, arrow)** improves workflow.

Diagnostic imaging ensues with the devices registered in MRI space for stereotactic targeting. For catheter insertion, the table is withdrawn, and needles inserted based on navigation software (Aegies, Hologic Inc.). The table is translated to isocenter for imaging verification every 1-3 catheters until the implant is complete. High-resolution images are then acquired for treatment planning of HDR brachytherapy. During treatment planning, the table is undocked, and the magnet driven out of the shielded brachytherapy suite. Once MRI safe, doors to the equipment room can be opened and the HDR afterloader can be connected to the catheters. Delivery proceeds with the patient under anesthesia, and all staff outside the treatment room. After radiation is delivered, catheters are removed and the patient is recovered. The overall procedure time is approximately 2 hours.

The imaging protocol includes diagnostic T2w TSE (TE: 103 ms; TR 5280 ms; 20 x 20 cm FOV with 320 x 320 matrix for 0.6 mm in-plane resolution; 2 mm slice thickness; 40 slices for 80 mm coverage; R/L phase encoding with 100% phase oversampling; iPAT factor 2; 200 Hz/pixel readout bandwidth; turbo factor 25; 2 averages; scan time 4 min 47 sec), and diagnostic DWI (TE 100 ms; TR 4000 ms; 20 x 20 cm FOV with 128 x 128 matrix for 1.6 mm in-plane resolution; A/P phase-encoding with 30% phase oversampling and 6/8 phase partial fourier; 3 mm slice thickness; 10 slices for 30 mm coverage; iPAT factor 2; 1148 Hz/pixel readout bandwidth; fat saturation; isotropic diffusion sampling; 4 b-values of 0, 100, 600, 1000 s/mm^2; 8 averages; scan time 5 min 34 sec). The transperinal template is also imaged for registration and navigation (TE 95 ms; TR 2000 ms; 18 x 18 cm FOV with 256 x 256 matrix for 0.7 mm in-plane resolution; A/P phase-encoding with 50% phase oversampling; 4 mm slice thickness; 5 slices for 20 mm coverage; iPAT factor 2; 199 Hz/pixel readout bandwidth; turbo factor 25; 3 averages; scan time 1 min 42 sec). Needle position is verified using short TSE imaging (TE 11 ms; TR 1300 ms; 20 x 20 cm FOV with 256 x 256 matrix for 1.0 x 0.8 mm in-plane resolution; R/L phase encode with 100% phase oversampling; 3 mm slice thickness; 14 slices for 42 mm coverage; iPAT factor 2; 190 Hz/pixel readout bandwidth; turbo factor 10; 1 average scan time 31 sec). Finally, images are acquired for treatment planning once catheters are locked in placed. (Axial TSE: TE 108 ms; TR 5760 ms; 18 x 18 cm FOV with 320 x 320 matrix for 0.6 mm in-plane resolution; R/L phase encoding; with 80% phase oversampling; 2 mm slice thickness; 46 slices for 92 mm coverage; 200 Hz/pixel readout bandwidth; turbo factor 20; 3 averages; scan time 8 min 51 sec).

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Insights

In this section, you will learn more about the functionality and advantages of MRI and its special use in Radiation Therapy (RT).

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