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Permanent Prostate Brachytherapy Post-Implant MRI Dosimetry Using Positive Contrast MRI Markers

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Abstract

Background/Purpose—Permanent prostate brachytherapy dosimetry using CT-MRI fusion combines the anatomic detail of MRI with seed localization on CT, but requires multimodality imaging acquisition and fusion. The purpose of this study was to compare the utility of MRI only post-implant dosimetry to standard CT-MRI fusion based dosimetry.

Methods—Twenty-three patients undergoing permanent prostate brachytherapy with use of positive contrast MRI markers were included in this study. Dose calculation to the whole prostate, apex, mid-gland, and base was performed via standard CT-MRI fusion and MRI only dosimetry with prostate delineated on the same T2 MRI sequence. The 3-dimensional distances between seed positions of these 2 methods were also evaluated. Wilcoxon matched-pair signed-rank test compared the D90 and V100 of the prostate and its sectors between methods.

Results—The day zero D90 and V100 for the prostate were 98% vs. 94% and 88% vs. 86% for CT-MRI fusion and MRI only dosimetry. There were no differences in the D90 or V100 of the whole prostate, mid-gland or base between dosimetric methods ($p > 0.19$), but prostate apex D90 was higher 13% with MRI dosimetry ($p = 0.034$). The average distance between seeds on CT-MRI fusion and MRI alone was 5.5 mm. After additional automated rigid registration of 3D seed positions the average distance between seeds was 0.3 mm, and the previously observed differences in apex dose between methods was eliminated ($p > 0.11$).

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Conflicts of interest: C4 imaging: SJF is founder and director. Varian: SJF is consultant/advisor.

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Conclusion—Permanent prostate brachytherapy dosimetry based only on MRI using positive contrast MRI markers is feasible, accurate, and reduces the uncertainties arising from CT-MRI fusion abating the need for post-implant multimodality imaging.

Keywords

prostate; brachytherapy; MRI; dosimetry

Introduction

Permanent low dose rate (LDR) prostate brachytherapy is one treatment option available to prostate cancer patients which is able to provide excellent disease control and an acceptable toxicity profile (1-3). Multiple studies have demonstrated that to achieve optimal disease outcomes with this technique the prostate D90 or V100 should be greater than 90% (4-6). Traditionally these post-implant dosimetric quality indicators have been determined by obtaining a CT scan of the pelvis after the procedure to identify the location of the brachytherapy seeds and anatomic boundaries of the prostate, urethra, bladder and rectum. There is, however, large interobserver variability in defining anatomic structures on CT leading to increased contour and dose variability (7). More recently, MRI has been introduced into the post-implant quality assessment process as it is able to provide improved soft tissue contrast and reduce observer variability in identifying multiple structures in the pelvis including the prostate, urethra, penile bulb, neurovascular bundles, and external urinary sphincter (8, 9). While MRI provides significant advantages in anatomic delineation compared to CT, accurate identification of brachytherapy seed locations on MRI alone remains challenging secondary to local magnetic field distortions produced by the seeds, MRI image acquisition variability, and decreased seed-prostate contrast.

Instead, CT and MRI are often combined for post-implant dosimetric analysis with the use of CT-MRI fusion. This allows for the utilization of seed localization on CT combined with improved anatomic detail on MRI. CT-MRI fusion has been shown to be feasible and provide small deviations in CT-MRI bony landmark alignment (10, 11). CT-MRI fusion is encouraged in the 2012 ABS prostate brachytherapy guidelines (12), yet uncertainties in CT-MRI fusion can be associated with significant variability in D90 of up to 16% (7). Studies investigating the use of various MRI sequences for identification of prostate brachytherapy seed positions without the use of CT are few and have been limited by heterogeneous MRI protocols, difficulty with detecting extraprostatic seeds (13), and the need for multiple MRI sequences with and without contrast for seed detection and organ contouring (7, 14, 15).

To address the problem of prostate brachytherapy seed identification on MRI, Frank et al have developed positive contrast prostate brachytherapy MRI markers (16). The marker utilizes the paramagnetic properties of 1% cobalt-dichloride-N-acetyl cysteine to produce a positive contrast on MRI. The markers are positioned between prostate brachytherapy seeds within a brachytherapy strand at the positions of traditional strand spacers allowing for potential seed identification on MRI. Preclinical studies have confirmed the ability of the markers to produce positive contrast in phantoms, and have identified appropriate MRI sequences for identification of the markers (17). These markers demonstrate minimal

potential biotoxicity (18), are FDA approved, and have been implemented into our prostate brachytherapy program at our institution. The purpose of this study was therefore to report on the ability to perform MRI only based dosimetry with the use of these markers and compare dosimetric outcomes to prostate brachytherapy seed identification on CT with subsequent CT-MRI fusion.

Methods

Patient Characteristics

Consecutive prostate cancer patients undergoing permanent prostate brachytherapy at our institution were evaluated for the possibility of utilizing the positive contrast MRI markers in their prostate brachytherapy implant. Patients were deemed prostate brachytherapy monotherapy candidates if they were found to have low or intermediate risk prostate cancer (PSA <15, Gleason score <8, and <T3 disease), and prescription brachytherapy doses for monotherapy were 144 Gy, 125 Gy and 115 Gy for implants using iodine, palladium, and cesium respectively. Patients could also be treated with a prostate brachytherapy boost using palladium (prescription dose 100 Gy) along with external beam radiation therapy for high risk disease (PSA ≥15, Gleason score ≥8, or T3 disease). All patients had staging workup with biopsy of the prostate confirming the diagnosis of prostate cancer and diagnostic pelvic MRI. Additional workup was implemented as necessary per physician and patient preference. Further eligibility for brachytherapy was determined for each patient prior to the procedure by performing pre-operative CT scan and ultrasound volume study to assess for pubic arch interference as described in prior reports (19). After prostate brachytherapy implantation, patients underwent a pelvic CT scan and MRI the day of the procedure (day 0) for treatment planning, to determine dosimetric parameters such as prostate D90 and V100. The dosimetric parameters were determined from MRI only or CT-MRI fusion as described below.

CT and MRI Sequences

Day 0 axial pelvic CT scan was acquired utilizing 2.5 mm slice thickness. MRI sequences included an axial 3D fast spin echo T2-weighted image and an additional image sequence for identification of the positive contrast MRI marker positions. Throughout the course of this investigation two different MRI sequences were used for MRI specific brachytherapy strand marker identification depending on the type of MRI scanner used. These were a 3D fast spoiled gradient echo (FSPGR) sequence used with a 3T General Electric Signa HDxT scanner and a 3D axial fast low angle shot (FLASH) sequence used with a 1.5T Siemens MAGNETOM Aera scanner (20, 21). The MRI parameters for the FSPGR sequence were repetition time (TR) = 6.18, echo time (TE) = ~3.3 ms, flip angle = 20°, number of excitations (NEX) = 8, field of view (FOV) = 14 cm, imaging matrix = 256×256, and slice thickness = 2 mm, while MRI parameters for the FLASH sequence were TR = 6, TE = 2.38, flip angle = 25°, FOV = 15 cm, imaging matrix = 256×256, and slice thickness = 1-2 mm. The FSPGR sequences used an inflatable endorectal coil while FLASH sequences used Invivo (Invivocorp, Gainesville, FL) MRI rigid endorectal. Prior to the FSPGR or FLASH sequences 1mg of glucagon was injected intramuscularly to suppress rectal contractions.

Dosimetric Parameter Determination

Anatomic delineation of the prostate gland and organs at risk was performed by an experienced Radiation Oncologist (SJF) on day 0 axial 3D fast spin echo T2-weighted images for all patients, using the FDA approved brachytherapy planning software, MIM Symphony (MIM Software Inc, Cleveland, OH). The positions of the brachytherapy seeds on day 0 CT scan were determined using MIM's auto brachytherapy seed segmentation algorithms followed with manual correction by an experienced brachytherapy dosimetrist as needed. The CT derived brachytherapy plans were then manually fused with the aforementioned anatomically delineated day 0 axial 3D fast spin echo T2-weighted images to determine the dosimetric quality parameters including prostate gland D90 and V100. CT-MRI fusion was performed by a dedicated brachytherapy dosimetrist utilizing information from CT seed positions, brachytherapy strand/seed hypointensities found on T2 weighted MRI, and patient anatomy on both scans (bony structures, prostate, rectum, etc) to help account for potential differences between the 2 imaging methods (e.g. use of endorectal devices on MRI).

The position of brachytherapy seeds on the day 0 MRI were determined manually by a radiation oncologist, physicist or brachytherapy dosimetrist on the appropriate FSPGR or FLASH sequences utilizing information from the positive contrast MRI markers for determination of interseed spacer location and subsequent radiation seed location (Figure 1). These MRI generated brachytherapy plans on the FSPGR or FLASH sequences were then fused to the anatomically delineated day 0 axial 3D fast spin echo T2-weighted images for MRI only dosimetric evaluation. Manual editing of the fusion between the 2 different MRI sequences was not performed as identical MRI geometric parameters were used between the two sequences including field of view, axial scan slice thickness, and prompt sequential acquisition of the scans. For both CT and MRI derived brachytherapy plans a line model of dose source as suggested by AAPM Task Group No. 64 was used (22).

CT-MRI vs. MRI only Dosimetric Evaluation

Post implant treatment plan dosimetry parameters prostate D90, V100, and V150 along with urethral V200 and rectal V100 (absolute volume) based on T2 contours were compared between the CT-MRI fusion and MRI only plans for each patient. Sector analysis was also performed in MIM Symphony to determine if there were significant dosimetric differences at the prostate gland base, mid-gland, or apex using similar methods as described in a previous publication (23). The Radiation Oncology team performing the post-implant dosimetry was blinded to the final dosimetric results of each modality to remove bias concerning the order that dosimetry was performed (i.e. CT-MRI based dosimetry first and vice versa).

The three-dimensional positions of the brachytherapy seeds determined on CT after CT-MRI fusion were also compared to their position when identified using only MRI sequences. All coordinates were expressed in the same T2 MRI coordinate system. To assess for potential CT-MRI fusion error or bias, the three dimensional seed locations were compared between the 2 methods after performing an additional automated 6-degree of freedom rigid registration (translation and rotation) using only seed position information and not

anatomical details. Each seed defined on CT was assigned uniquely to the nearest seed on MRI using k-nearest neighbor classification, and these assignments were used to generate the 3-dimensional distances between seeds both before and after the automated registration of the 3D seed distributions. These analyses were performed using MATLAB version R2014b (The Mathworks, Natwick, MA).

Statistical Analysis

Due to the population sample size and within individual comparisons, the dosimetric variables (D90, V100, V150, etc) are reported as the median with the interquartile range (25th – 75th percentile), and the statistical evaluation between these variables was performed using a non-parametric Wilcoxon matched-pair signed-rank test. For the distances between seed positions using the 2 methods, the mean ($\pm$ standard error of the mean (S.E.)) is reported, and a one-sample t-test was used to compare the means of these differences with a null hypothesis mean of 0. Two sided p-values < 0.05 were considered statistically significant. Statistical analysis was performed using SPSS version 23 (IBM, Armonk, NY).

Results

Patient Characteristics

Twenty-five consecutive patients in 2014 and 2015 were evaluated for potential use of the positive contrast MRI markers, with twenty-three patients ultimately available for analysis in this study. Two patients underwent brachytherapy implant at our institution over this same time period but positive contrast MRI marker were not used in their procedure since they were unable to have MRI performed, and one patient's day 0 MRI was of poor quality precluding seed identification. Otherwise all 23 patients had a day 0 CT and MRI performed, with MRI being performed on average 3 hours after the CT. The average age of patients in the study was 63.7 years old. Twenty-one patients had prostate brachytherapy as monotherapy for definitive treatment of their prostate cancer, and 2 patients had brachytherapy as part of a boost after treatment with external beam radiation therapy for high risk disease. Twelve patients had Iodine-125 (I-125), 3 had Palladium-103 (Pd-103), and 8 had Cesium-131 (Cs-131) isotopes used in their prostate brachytherapy implants respectively. The remaining characteristics of this patient population can be found in Table 1.

CT-MRI Fusion vs. MRI only Dosimetric Evaluation

An example of dosimetry performed on MRI and CT with 3D fast spin echo T2-weighted images derived contours utilized in both methods is depicted in Figure 2. The median (interquartile range (IQR)) D90 for the whole prostate was 100% (87-108%) when calculated using CT-MRI based dosimetry, and 99% (84-108%) when using MRI alone ($p = 0.38$). The median (IQR) V100 for the whole prostate was 91% (85-93%) when calculated using CT-MRI based dosimetry, and 90% (82-94%) when using MRI alone ($p = 0.30$). The median (IQR) prostate V150 was 47% (38-58%) when calculated using CT-MRI based dosimetry and 50% (47-55%) when using MRI alone ($p = 0.094$), the median (IQR) urethral V200 was 0.04% (0-2.88%) when calculated using CT-MRI based dosimetry and 0.02% (0-1.65%) when using MRI alone ($p = 0.18$), and the median (IQR) rectal V200 was 0.78

mL (0-3.28 mL) when calculated using CT-MRI based dosimetry and 0.59 mL (0-1.34 mL) when using MRI alone ($p = 0.014$).

Sector analysis of the prostate apex, mid-gland, and base was also performed using the two different dosimetric methods (Figure 3). Similar to whole prostate gland dosimetry there was no statistically significant difference in the D90 or V100 between CT-MRI and MRI only based dosimetry of the prostate mid-gland and base ($p > 0.08$). There was, however, a statistically significant difference in the D90 to the prostate apex between the 2 dosimetric methods, with a median (interquartile range) apex D90 of 112% (95-119%) using CT-MRI fusion dosimetry vs. 115% (103-135%) using MRI only based dosimetry ($p = 0.001$), and median (interquartile range) apex V100 of 94% (87-99%) and 99% (92-100%) using CT-MRI fusion and MRI only dosimetry respectively ($p = 0.03$).

Sub-group analyses showed that patients who had MRI post-implant dosimetry using the inflatable endorectal coil had statistically significant difference in mid-prostate V100 and apex D90 when these dosimetric values were determined via CT-MRI fusion vs. MRI only ($p < 0.03$), while patients with the Invivo rigid endorectal coil only showed difference in apex D90 when compared between the 2 methods ($p = 0.03$). There were otherwise no differences in whole prostate or sector D90 and V100 between CT-MRI fusion and MRI only dosimetry ($p > 0.06$). No differences were seen in prostate dosimetric variables between CT-MRI fusion or MRI only based methods when analyzed by isotope type. The number of needles or seeds used in the brachytherapy implant, the pre-implant prostate ultrasound volume, and pre-implant PSA were also not associated with post-implant prostate D90 or V100 as determined by either dosimetric method.

Spatial Distribution of Brachytherapy Seeds Determined by CT-MRI Fusion vs. MRI only Techniques

The mean ($\pm$ S.E.) distance between seeds defined on CT-MRI fusion vs. MRI alone was 5.53 mm (± 0.38 mm) after manual anatomical fusion. Separating the calculated spatial distances into their anterior-posterior, left-right, and superior-inferior components led to mean ($\pm$ S.E.) distances between the two methods of 1.21 mm (± 0.39 mm), 0.48 mm (± 0.54 mm), and 5.62 mm (± 0.77 mm) in those axes respectively. There was no statistically discernable difference between the seed locations calculated in the left-right axes ($p = 0.39$), but this difference was significant in the anterior-posterior and superior-inferior direction ($p = 0.005$), with seed positions on CT-MRI fusion being located more anteriorly and superiorly. After registering brachytherapy seed positions defined on CT-MRI fusion to those on MRI alone using automated rigid registration of seed position information only, the mean ($\pm$ S.E.) spatial difference was 0.19 mm (± 0.01 mm), with differences of 0.17 mm (± 0.13 mm) in the anterior-posterior axis, 0.17 mm (± 0.13 mm) in the left-right axis, and 0.01 mm (± 0.1 mm) in the superior-inferior axis with no statistical difference in any of these planes ($p > 0.18$). The D90 and V100 to the prostate and its sectors was re-calculated for the registered CT-MRI fused seed positions, and the previously noted difference in apex D90 and V100 between the 2 dosimetric methods was no longer statistically significant ($p > 0.11$). An example of the 3-dimensional seed locations and dosimetric calculations before and after registration of the seed positions is depicted in Figure 4. Moreover, due to the use of

endorectal devices during MRI but not CT, the spatial locations of the 1/4 most posterior brachytherapy seeds were also compared after registering the seed positions between the two methods (CT-MRI fusion vs. MRI alone), and there was no statistical difference in their locations in any plane ($p = 0.25$).

Discussion

This is the first study to our knowledge to evaluate the dosimetric utility of MRI only quality assurance using positive contrast MRI brachytherapy strand markers in patients undergoing permanent prostate brachytherapy implantation. The results from this study show that MRI only post-brachytherapy dosimetry with stranded implants is not only feasible, but provides similar D90 and V100 calculations compared to dosimetry performed by CT-MRI fusion. The difference in reported apex D90 and V100 between the 2 methods was eliminated after additional automated registration of the seed locations with no statistically significant variation in the spatial distribution of the seed positions. These results therefore suggest that MRI only post-implant dosimetry may be more reliable than CT-MRI fusion by reducing the uncertainties stemming from the fusion process. The ability to perform MRI only day 0 dosimetric calculations was likewise successful using two different MRI protocols regardless of brachytherapy isotope selection, seed number, or other clinical factors.

Post-implant dosimetry remains an important part of the brachytherapy quality assurance process that not only allows for possible modification of treatment with addition of brachytherapy seeds if target coverage is deemed sufficiently inadequate, but also gives potential information on general quality of the implant, probability of disease control and expected organ at risk toxicities. Uncertainties in a variety of parameters such as brachytherapy seed location/orientation, prostate/organ at risk (OAR) boundary delineation, etc can lead to degradation in the quality of the process. MRI potentially helps improve this process by providing more consistent, accurate prostate gland and organ at risk identification as has been shown by numerous studies showing prostate volumes on CT are 16-40% bigger compared to MRI (7, 24, 25), and that intraobserver and interobserver variability of prostate volume delineation on CT can be 74% and 41% higher than MRI respectively (25). The effects of post-implant edema on prostate volume has also been shown to be less apparent with MRI as one study showed 2-week post-implant CT volume to be 28% larger compared to pre-implant CT volume but prostate volume was only 12% larger when comparing 2-week post-implant MRI to pre-implant MRI (26). The dosimetric impact of contouring uncertainty has been shown to lead to D90 variation up to 23% (7), and prostate contour uncertainty has been identified as a major potential cause of radiobiological outcome uncertainty following I-125 brachytherapy implantation (27).

Multiple investigations in recent years have reported on the ability of MRI only prostate post-brachytherapy dosimetric evaluation (13-15). Most of these studies have focused on MRI protocols utilizing contrast enhanced sequences due to generally poor identification of brachytherapy seeds on T2 weighted images alone (28). In particular, Tanaka et al utilized contrast enhanced T1 weighted MRI images for manual identification of brachytherapy seeds and showed that MRI based prostate D90 and V100 exhibited R^2 values of 0.81 and 0.80 compared to identification of brachytherapy seeds on CT with subsequent CT-MRI

fusion (13). MRI based dosimetry in this study showed increased prostate V200, V150, V100, and D90, but MRI based seed detection was only able to detect 78% of extra prostatic seeds. Another study from Japan also utilized contrast enhanced T1 weighted images to manually identify prostate brachytherapy seeds and showed similar correlation between MRI and CT based prostate V100 and D90 (intraclass correlation coefficient (ICC) = 0.73-0.80, $p=0.08-0.1$) (15). There was a noted decrease in anterior base prostate coverage and a statistically significant decrease in prostate V150 with MRI dosimetry compared to CT in this study, but no other dosimetric differences in prostate sectors. More recently Buch et al utilized automated brachytherapy seed detection on contrast enhanced T1 weighted MRI sequences to show that prostate V100 and D90 were lower by 2% and 10% respectively ($p<0.05$) using MRI based dosimetry compared to CT. Some caution must be utilized when interpreting these results, however, as CT based dosimetry in this study was performed on contours derived from CT scans and not from MRI in the CT-MRI fusion potentially introducing dosimetric differences based upon contouring differences between the imaging modalities (14). Additionally, non-contrast T1 weighted images have been used for brachytherapy seed identification and De Brabandere et al have shown MRI based seed reconstruction interobserver variability in D90 of 7% using this technique (7).

The results from this study add to the aforementioned body of literature by demonstrating the ability to perform MRI only based dosimetry utilizing brachytherapy strands with a positive contrast MRI marker. Our results show similar whole prostate D90 and V100 between CT-MRI and MRI only based dosimetry. Sector analysis initially showed differences in prostate apex dose between the 2 methods, however, after registering the 3-dimensional brachytherapy seed locations from CT-MRI fusion to the seed positions determined on MRI alone, this disparity disappeared with no discernible differences in the 3-dimensional distribution of seeds determined by the 2 methods. Focusing only on the $\frac{1}{4}$ most posterior seeds, we also found no difference in these seeds' locations after registration when identified on CT vs. MRI, suggesting that the use of endorectal devices (either inflatable or rigid) during MRI does not likely significantly impact dosimetric calculations. It should be noted that these devices may cause increased difficulty in the fusion process between CT and MRI or cause other prostate organ deformations not appreciated by brachytherapy seed locations, yet endorectal devices are currently necessary to obtain adequate MRI images sufficient for MRI only post-implant dosimetry using this approach and potentially limits the generalizability of these results to CT-MRI fusion uncertainties without an endorectal coil (20). Further analysis to precisely quantify the prostate deformation caused by these endorectal devices is also currently underway by our group. Ultimately, these results emphasize the uncertainty surrounding manual CT-MRI fusion for determining post-brachytherapy dosimetry, and gives credence to MRI only dosimetry as a viable and potentially preferred method of post-brachytherapy dosimetric calculation.

Our study does have a few limitations including its small sample size. Both the timing of the CT and MRI scans and the way in which the scans were acquired could also contribute to alterations in the images which could confound our ability to compare CT and MRI based plans. In particular, the CT and MRI sequences were acquired on average 3 hours apart with the possibility for changes in prostate edema, patient positioning, rectal and bladder filling to affect prostate positioning and CT-MRI fusion quality. We believe that the effect of edema or

rectal device differences likely played a minor role, however, with regards to dosimetric differences between the methods given that automated registration showed no evidence of systemic seed location differences, and a prior study by Dinkla et al demonstrated small edema changes in the first 2 days after implantation of prostate catheters (29). Furthermore, the time to generate the MRI only plans by the dosimetrists and radiation oncologists was also not prospectively evaluated and compared to CT-MRI fusion, thus not allowing us to evaluate the efficiency of this approach. Finally, we did not perform this same analysis on day 30 post-brachytherapy scans as many patients did not have both day 30 MRI and CT. Multiple other investigations have confirmed decreased day 0 prostate dose compared to day 30 due to edema effects (30, 31), and this may also translate into differences in CT-MRI fusion quality. Despite these limitations our study was able to demonstrate the utility of MRI based dosimetry compared to CT based dosimetry with MRI fusion, and our group is currently investigating less distorting endorectal coils, refinement of the MRI sequences, and MRI based auto seed identification to address some of the aforementioned concerns.

In conclusion, we have shown that MRI only based dosimetry with positive contrast MRI brachytherapy strand markers is feasible and provides accurate prostate dosimetric results compared to CT-MRI fusion. The use of MRI only dosimetry avoids potential uncertainties introduced in CT-MRI fusion, allows for more seamless integration of scans used for post-brachytherapy dosimetry and contouring, and brachytherapy provides an excellent environment for the incorporation of MRI given the local nature and non-CT dependent calculation of dose deposition. Continued refinement of the MRI sequences, MRI endorectal coils, and MRI seed identification will hopefully allow for more accurate and efficient post-brachytherapy MRI based planning in the future and remains an area of active research.

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Abbreviations

LDR	Low dose rate
CT	Computed tomography
MRI	Magnetic resonance imaging
D90	Dose to 90% of a specified anatomic volume
V100	Volume of a specified anatomic structure receiving 100% of the prescription dose
PSA	Prostate-specific antigen
mm	Millimeters
AAPM	American Association of Physicists in Medicine
S.E.	Standard error of the mean
3D	3-dimensional
ICC	Intraclass correlation coefficient

Figure 1.

Example of brachytherapy marker identification on FSPGR and FLASH sequences. Slices depicted are axial representations from day 0 post-brachytherapy MRI in 2 different patients at the level of the mid-pubic symphysis. FSPGR sequence is depicted on the left and FLASH sequence is depicted on the right. Representative positive MRI contrast brachytherapy markers are identified with red circles and brachytherapy seed signal voids are depicted in yellow circles. An endorectal coil was used in both image sets.

Figure 2.

Example of T2 axial, sagittal, and coronal images of post-brachytherapy dosimetry in one patient. Panel A shows prostate contour delineated on T2-weighted image sequence (blue line). Panel B depicts dosimetry when brachytherapy seeds were identified on CT with subsequent CT-MRI fusion, and panel C shows dosimetry when brachytherapy seeds were identified on MRI alone. FLASH MRI sequence was used to identify seed positions on MRI alone plan in this patient. Prostate was contoured on the same axial T2 weighted image (panel A) and fused to appropriate CT and FLASH sequences for dosimetric analysis. Isodose lines as percentage of prescription dose are depicted in the figure legend in panel A.

Figure 3.

Box plots of D90 and V100 of prostate and sector contours computed via CT-MRI fusion vs. MRI only post-implant dosimetric analysis. The horizontal lines represent the median value and the lower and upper error bars represent the 25th and 75th percentiles respectively. Wilcoxon rank analysis did not show any statistically significant differences between any of the depicted dosimetric parameters on CT-MRI fusion vs. MRI only ($p > 0.07$) except for apex D90 ($p = 0.001$) and V100 ($p = 0.03$).

Figure 4.

Brachytherapy seed and dose 3-dimensional distributions for one patient before and after seed position fusion. Panels on the left depict the 3-dimensional brachytherapy seed positions as determined on MRI (red circles) vs. those determined on CT (blue circles) after CT-MRI fusion. The right panels depict 100% prescription isodose cloud (red) around the prostate (blue) and prostate apex (yellow). A and B) CT seed positions and isodose cloud are depicted after manual anatomical fusion (i.e. CT to T2 MRI) but before additional 3D registration to MRI seed positions. C and D) CT seed positions and isodose cloud auto-registered to MRI using only 3D seed positions. X, Y, and Z in panels A and C represent the left-right, anterior-posterior, and superior-inferior axis of the patients respectively.

Table 1
Baseline patient characteristics

Age at time of implant (years), average ($\pm$ S.D.)	63.8 ($\pm$ 7.7)
Clinical tumor stage, n (%)	
T1c	19 (83%)
T2a	4 (17%)
Pre-brachytherapy PSA (ng/mL), average ($\pm$ S.D.)	6.1 ($\pm$ 2.4)
Pre-brachytherapy Gleason score, n (%)	
6 (3 + 3)	4 (18%)
7 (3 + 4)	12 (52%)
7 (4 + 3)	5 (22%)
8 (4 + 4)	1 (4%)
9 (4 + 5)	1 (4%)
Brachytherapy isotope, n (%)	
Cesium-131	8 (35%)
Iodine-125	12 (52%)
Palladium-103	3 (13%)
Brachytherapy needles, average ($\pm$ S.D.)	25.5 ($\pm$ 3.8)
Brachytherapy seeds, average ($\pm$ S.D.)	81.3 ($\pm$ 14.9)
Post-brachytherapy prostate MRI volume (mL), average ($\pm$ S.D.)	42.3 ($\pm$ 15.8)
Post-brachytherapy MRI sequence, n (%)	
FSPGR	14 (61%)
FLASH	9 (39%)
Post-brachytherapy MRI endorectal coil device, n (%)	
Inflatable endorectal coil	15 (65%)
Invivo rigid endorectal coil	7 (31%)
None	1 (4%)

S.D. - standard deviation