Interstitial rotating shield brachytherapy for prostate cancer
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Purpose: To present a novel needle, catheter, and radiation source system for interstitial rotating shield brachytherapy (I-RSBT) of the prostate. I-RSBT is a promising technique for reducing urethra, rectum, and bladder dose relative to conventional interstitial high-dose-rate brachytherapy (HDR-BT).

Methods: A wire-mounted 62 GBq 153Gd source is proposed with an encapsulated diameter of 0.59 mm, active diameter of 0.44 mm, and active length of 10 mm. A concept model I-RSBT needle/catheter pair was constructed using concentric 50 and 75 μm thick nickel-titanium alloy (nitinol) tubes. The needle is 16-gauge (1.651 mm) in outer diameter and the catheter contains a 535 μm thick platinum shield. I-RSBT and conventional HDR-BT treatment plans for a prostate cancer patient were generated based on Monte Carlo dose calculations. In order to minimize urethral dose, urethral dose gradient volumes within 0–5 mm of the urethra surface were allowed to receive doses less than the prescribed dose of 100%.

Results: The platinum shield reduced the dose rate on the shielded side of the source at 1 cm off-axis to 6.4% of the dose rate on the unshielded side. For the case considered, for the same minimum dose to the hottest 98% of the clinical target volume (D98%), I-RSBT reduced urethral D0.1cc below that of conventional HDR-BT by 29%, 33%, 38%, and 44% for urethral dose gradient volumes within 0, 1, 3, and 5 mm of the urethra surface, respectively. Percentages are expressed relative to the prescription dose of 100%. For the case considered, for the same urethral dose gradient volumes, rectum D1cc was reduced by 7%, 6%, 6%, and 6%, respectively, and bladder D1cc was reduced by 4%, 5%, 5%, and 6%, respectively. Treatment time to deliver 20 Gy with I-RSBT was 154 min with ten 62 GBq 153Gd sources.

Conclusions: For the case considered, the proposed 153Gd-based I-RSBT system has the potential to lower the urethral dose relative to HDR-BT by 29%–44% if the clinician allows a urethral dose gradient volume of 0–5 mm around the urethra to receive a dose below the prescription. A multisource approach is necessary in order to deliver the proposed 153Gd-based I-RSBT technique in reasonable treatment times. © 2014 American Association of Physicists in Medicine.

Key words: brachytherapy, rotating shield brachytherapy, intensity modulated brachytherapy

1. INTRODUCTION

Patients with localized prostate cancer are typically treated with external beam radiotherapy (EBRT) alone, EBRT in combination with high-dose-rate brachytherapy (HDR-BT), EBRT in combination with low-dose-rate brachytherapy, or EBRT in combination with pulsed-dose-rate brachytherapy. Radical prostatectomy is also a treatment option. Radiotherapy techniques are associated with greater bowel toxicity than radical prostatectomy. Surgery carries a greater risk of urinary incontinence than radiotherapy and possibly higher sexual dysfunction rates. Regardless of the treatment technique, 5-year relative survival rates are typically above 90% and anticipated complications are important in selecting the appropriate treatment technique for prostate cancer.

Brachytherapy techniques have been reported to provide lower rectal toxicity than EBRT techniques, and combined EBRT and HDR-BT have been shown to have greater late genitourinary toxicity than EBRT alone. In a recent study comparing the toxicities of localized prostate cancer patients treated with image guided EBRT, combined EBRT and HDR-BT, and BT monotherapy it was reported that combined EBRT and HDR-BT had the highest late (>6 months after treatment) genitourinary toxicity of grade 3 or higher (4% vs 12% vs 5%, p < 0.001) and ranked in the middle for late gastrointestinal toxicity of grade 2 or higher (20% vs 9% vs 2%, p < 0.001). Of particular concern in combined EBRT and HDR-BT treatments are the grade ≥ 3 urethral stenosis.
rates, which have been reported to be in the range of 7%–10% by multiple centers,4,5,23,24 and of greater severity than those from EBRT alone.3

Conventional interstitial HDR-BT techniques use radiation sources with dose distributions that are radially symmetric about the catheter axis.25 Tumor dose conformity and organ-at-risk doses are sensitive to the number of catheters used, the locations of the catheters, and the tumor geometry. If it was possible to determine the optimal number of catheters, catheter locations, and source dwell times for a given HDR-BT case, the resulting dose distribution would still only be optimal under the constraint that the source emits radially symmetric dose distributions. Interstitial rotating shield brachytherapy (I-RSBT) is a novel form of high-dose-rate brachytherapy (HDR-BT) delivered through shielded, rotating catheters.26–28 I-RSBT removes the constraint that dose distributions must be radially symmetric about each individual catheter. I-RSBT thus has the potential to provide unprecedented control over radiation dose distributions.

When I-RSBT was first conceptualized,26 specific radiation sources that are amenable to shielding were not identified, and satisfying the need is a major challenge. Delivering I-RSBT with clinically acceptable dose rates necessitates the development of novel radiation sources. A conventional 192Ir source is not feasible for I-RSBT delivery since its radiation transmission, even through 1.5 mm of platinum, would be about 60%. Such a high transmission was demonstrated to be suboptimal for RSBT by Ebert in the first theoretical consideration of the technique,29 and such a shield is thicker than the thickest shield that could fit inside a 16 gauge catheter (1.651 mm diameter) while still leaving room for the radiation source. Low-energy brachytherapy sources such as 125I and 103Pd, where photoelectric interactions are dominating, are attenuated strongly in tissue and are not compensated by scatter. For intermediate sources such as 153Gd, photoelectric interactions are minimal. Attenuation in tissue is compensated for by scatter build up factor from low energy photons.

In this work, the 153Gd radioisotope is considered as an I-RSBT isotope with an appropriate specific activity and energy spectrum to enable its use in a 16-gauge shielded needle/catheter apparatus, with a similar radial dose function as 192Ir.28 153Gd emits primarily intermediate-energy photons in the 40–105 keV range, which are ideal for several reasons. First, the Compton effect is the dominant photon interaction in tissue for the 153Gd source, enabling straightforward ion chamber, film, and thermoluminescence dosimetry. Second, 153Gd attenuation in tissue is counteracted by single and multiple low energy photon scatter, yielding unshielded dose distributions with a similar radial dose function as 192Ir.28 Third, the tenth-value-layer (TVL) of 153Gd is 0.37 mm of platinum,28 which is small enough to enable the construction of shielded catheters of 16 gauge diameter or less, enabling safe application. Fourth, 153Gd can be produced with specific activities high enough to enable I-RSBT treatment times on the order of a few hours. Fifth, 153Gd has a half-life of 240 days, which is sufficiently long to reduce time- and labor-intensive source changes relative to 192Ir, which has a 74 day half-life. Sixth, mass production techniques for 153Gd are becoming available,28 creating the potential for widespread adoption.

I-RSBT may enable both a significant reduction in urethral stricture rates as well as the delivery of higher prostate dose under the same healthy tissue constraints relative to conventional HDR-BT. As urethral dose is closely associated with the incidence of Grade 2 or higher acute genitourinary toxicity,30–35 such an expectation is not unreasonable. In the current work a needle, catheter, and 153Gd source apparatus for delivering I-RSBT is defined, and the potential urethral, rectum, and bladder dose reductions of I-RSBT below conventional HDR-BT are investigated with a goal of assessing the capability of I-RSBT to reduce urethral dose relative to conventional HDR-BT.

2. MATERIALS AND METHODS

2.A. Source and shielded catheter design

A novel needle/catheter/source concept model system (Fig. 1) was constructed to enable I-RSBT delivery. The overall design of the system was a dual needle system, where an applicator allows entrance of the shielded catheter in which the source will be inserted. To enable this source design a key feature was the use of nitinol tubing for the needle and catheter. Nitinol is strong, thin, and flexible, enabling the availability of sufficient space for the rotating shield. The needle is a 16-gauge nitinol tube with a wall thickness of 75 μm. The 16-gauge needle was chosen as the smallest needle gauge that could be used with the proposed design such that the catheter, source, and shield fit within the needle. As 15.5 gauge plastic needles that are frequently used for traditional HDR-BT have diameters greater than those that would be used for I-RSBT, 16 gauge needles are clinically reasonable. The needle contains a nitinol catheter that can rotate and translate freely due to the presence of 50 μm of air space between the tubes. The catheter has a wall thickness of 50 μm and contains a platinum shield with a maximum thickness of 535 μm and a radiotranslucent aluminum emission window. The catheter contains a removable, wire-mounted, 153Gd source. The source was modeled but not constructed, and designed such that the active source had a 10 mm length and a 0.44 mm diameter, with a titanium encapsulation thickness of 75 μm. The simulated 153Gd source had an activity of 5550 GBq of 153Gd per gram of Gd.28 The platinum shield was constructed such that the 153Gd source was offset from the central axis of the catheter, maximizing the thickness of the shield under the constraint that the minimum achievable thickness of the aluminum window was 125 μm. The platinum shield, aluminum window, and nitinol tubing were laser beam welded together in a 13 psi argon gas environment.

The needle would be stabilized with a stylet during insertion and is ultrasound, magnetic resonance, and computed tomography imaging compatible, and sterilizable for multiple uses. Following the imaging and treatment planning process, the catheter would be inserted into the needle just prior to radiation delivery. During radiation delivery, the needle would remain stationary while the catheter is rotated and retracted.
FIG. 1. I-RSBT 17-gauge (a) clinical concept model catheter with platinum shield (dashed line) and aluminum cap (solid line), viewing ports were cut into the needle and catheter for demonstration purposes, (b) a 3D view of the system showing the entrance of the source into the platinum shield with the aluminum emission window, and (c) image generated from the MCNP model showing dimensions of the components and the offset position of the source within the catheter. OD: outer diameter. ID: inner diameter.

The nitinol needle and catheter are flexible to bending motion applied perpendicularly to their colinear axes, yet the catheter’s deformation is negligible when a twisting motion is applied to the proximal catheter. This is an advantageous property for a catheter used for I-RSBT delivery, as it is necessary to ensure that catheter rotations applied outside the patient result in the same rotations inside the patient.

A 153Gd source will have a substantially lower dose rate than an 192Ir source of the same volume.28 It is expected that 153Gd-based I-RSBT will only be clinically feasible if delivered using a multisource, multicatheter approach. It is assumed in the current work that an apparatus that simultaneously controls ten shielded 153Gd catheters for I-RSBT delivery can be feasibly constructed and clinically implemented. A detailed description of such a device is beyond the scope of the current work, and a prototype system is under development.

2.B. Monte Carlo dose calculations

Dose calculations were done using the Monte Carlo N-Particle Transport Code version 5 (MCNP5), with the energy deposition (F6) tally.26 The 155Gd photon spectrum was the same as that used by Enger et al.28 The shielded 155Gd source was positioned at the center of a spherical water phantom with a density of 0.998 g/cm³ and a radius of 40 cm, which simulated an unbounded phantom.28 The source was simulated as a pure gadolinium cylindrical active core with a length of 10 mm. The source was encapsulated by a titanium cylinder (ρ = 4.506 g/cm³) with a 0.59 mm outer diameter, similar in outer diameter to the clinically utilized 192Ir source (VariSource™, Varian Medical Solution, Inc., Palo Alto, CA).37

The shield was simulated as a platinum and iridium alloy with 90 and 10 weight percentages, respectively, a density of 21.45 g/cm³, and an emission angle of 180°. The radio-translucent emission window was simulated as pure aluminum with a density of 2.70 g/cm³. The needle and inner catheter were modeled as nitinol needles with Ni and Ti weight percentages of 55.6 and 44.4, respectively, densities of 6.54 g/cm³, and dimensions corresponding to a 16 gauge needle (outer diameter of 1.651 mm) and 17 gauge needle (outer diameter of 1.473 mm), respectively. The spaces surrounding the source wire and between the inner catheter and needle were modeled as air at 760 Torr with a density of 1.293 × 10⁻³ g/cm³. Tally cells were defined in a spherical coordinate system with both the zenith (θ) and azimuthal (φ) angular bin boundaries separated by 5°. The radial bin (r) boundary increments were 0.05 cm up to 3 cm away from the source, 0.1 cm from 3 to 5 cm, 0.25 cm from 5 to 10 cm, 0.5 cm from 10 to 20 cm, and 1 cm from 20 to 40 cm. The bin boundaries had a finer resolution than those recommended in the American Association of Physicists in Medicine Task Group Report 43UI,38 which recommends 10° zenith angle bin sizes and radial distances of 0.5, 1, 2, 3 and 5 cm, and 7 cm for 125I.

The number of starting 155Gd photons in the simulations was 10⁹, which was selected such that the dose-weighted relative error, σᵢdᵢ/d₀, was less than or equal to 0.011 for all voxels outside of the needle. The quantity σᵢ is the relative error
and $d_i$ is the dose rate in tally bin $i$. The quantity $d_0$ was the dose in the voxel at $(\theta, \phi, r) = (90^\circ, 0^\circ, 1 \text{ cm})$, which is in the center of the emission window on a line perpendicular to the source axis that passes through the center of mass of the active source.

The dose rate distribution of the unshielded $^{192}\text{Ir}$ was modeled in MCNP5 with same radial and zenith angle bins as the shielded $^{153}\text{Gd}$ source for the purpose of calculating conventional HDR-BT dose distributions. The $^{192}\text{Ir}$ source was modeled after the Varian VarianSource (Varian Medical Solution, Inc., Palo Alto, CA) as a pure iridium cylindrical active core with a length of 5 mm, an active diameter of 0.34 mm, and an outer wire diameter of 0.59 mm.\textsuperscript{37} The simulated $^{192}\text{Ir}$ source had an activity of 370 GBq.

**2.C. Treatment planning**

An anonymous prostate cancer patient was considered who was previously treated with conventional HDR-BT. Computed tomography images were used for the treatment planning process, and a total of 19 needles were used. The number of rotational angles used per dwell position was 16, and the spacing between dwell positions in a given needle was 5 mm. Dose delivery was modeled in a step-and-shoot fashion, where a catheter delivers dose for a given amount of time at each angular position for a given set of longitudinal positions.

The methods of the California Endocurietherapy Institute were used for prostate target volume definition and treatment planning.\textsuperscript{39} The prostate gland was contoured and the clinical target volume (CTV) was generated by adding a 5 mm margin to the prostate, but not for the prostate adjacent to the bladder and rectum, and the proximal seminal vesicles.\textsuperscript{39} For the case considered, the patient had a fairly average anatomy with a CTV of 60 cm$^3$. Organs at risk were the urethra, bladder, and rectum. Dosimetric requirements were the following. For the CTV, 100% $\leq$ $D_{90}$ $\leq$ 115%, 97% $\leq$ $V_{100}$ $\leq$ 100%, 150% $< 35\%$. In order to ensure a fair comparison between treatment plans, the CTV $D_{90\%}$ was set to 100% of the prescription dose for all treatment plans. The $D_{0.1cc}$ and $D_{1.0cc}$ values for the rectal wall were constrained to $< 85\%$ and $< 80\%$, respectively, and the values for the bladder wall were constrained to $< 100\%$ and $< 90\%$, respectively. The $D_{0.1cc}$ and $D_{1cc}$ values for the urethra and periapical urethra were constrained to $< 110\%$ and $< 105\%$, respectively.\textsuperscript{39}

The periapical urethra was considered in the treatment planning process since a correlation has been shown between prostate brachytherapy related urethral stricture and the volume of the periapical urethra receiving 150% of the prescription dose ($V_{150}$).\textsuperscript{40} Since the urethral and therefore periapical urethral $V_{150}$ is zero under the above prescription requirements, the periapical $D_{0.1cc}$ was reported instead of $V_{150}$ in order to be consistent with the dose-volume metric reported for the urethra.

Treatment plans for I-RSBT and HDR-BT were generated using an in-house gradient-based optimizer used in previous external beam radiotherapy\textsuperscript{41-43} and rotating shield brachytherapy\textsuperscript{44,45} studies. The optimizer uses the linear least squares method\textsuperscript{46} to determine the dwell time vector, $t$, that produces the dose distribution $d_i$, for all voxels $i$, which is calculated as

$$d_i = \sum_j D_{ij} t_j,$$

where $D_{ij}$ is the dose rate at voxel $i$ for a given source position and direction, indexed by $j$. The following quadratic objective function is minimized:

$$E(\vec{t}) = \sum_{k=1}^{K} \frac{1}{T_k} \sum_{i \in T_k} \left[ \beta_k^+ \overline{H}^2 (d_i^k - d_i^k^*) + \beta_k^- \overline{H}^2 (d_i^k - d_i^k) + \beta_k^{V_k} C_{(0, \Delta D_{V_k})} (d_i^k - d_i^{V_k}) \right],$$

subject to the constraint that $t_j \geq 0$ for all $j$, and the optimization parameters are defined in Table I. The function $H(x)$ of real number $x$ is a Heaviside function, where $H(x) = 0$ if $0 \leq x$ and otherwise, and $C_{(a,b)}(x) = x$ if $a \leq x \leq b$ and 0 otherwise. The optimization parameter values used for HDR-BT and I-RSBT are listed in Table II. After each optimization was completed, the resulting dose distribution was scaled such that 100% of the CTV received a dose of 98%.

It is expected that the shielded $^{153}\text{Gd}$ radiation sources will enable substantial urethral sparing relative to conventional HDR-BT, and that the magnitude of urethral dose reduction will increase if the clinician allows a urethral dose gradient volume around the urethra to receive a dose less than the prescription dose. The urethral dose gradient volumes consisted of the tissue between the urethra and urethral sparing margins (expansions) of 0, 1, 3, and 5 mm, inside which the dose was allowed to drop below the prescription dose. A separate set of treatment plans was generated using each margin.

<table>
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<th>Table I. Definitions of optimization parameters.</th>
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<td>Parameter</td>
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<td>$d_k^+$, $d_k^-$</td>
</tr>
<tr>
<td>$d_k^{V_k}$, $V_k^{+}$</td>
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<tr>
<td>$\Delta D_{k^{V_k}}$</td>
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<p>| Table II. Optimization parameters for I-RSBT and HDR-BT. P-Urethra is the periapical urethra. NT is normal tissue. N/A means not applicable. |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|</p>
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<th>$d_k^+$</th>
<th>$d_k^-$</th>
<th>$d_k^{V_k}$</th>
<th>$d_k^{+}$</th>
<th>$V_k^{+}$</th>
</tr>
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<td>0</td>
<td>N/A</td>
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<tr>
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<td>50%</td>
<td>0</td>
<td>120%</td>
<td>0</td>
<td>N/A</td>
</tr>
<tr>
<td>P-Urethra</td>
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<td>50%</td>
<td>0</td>
<td>120%</td>
<td>0</td>
<td>N/A</td>
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<tr>
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<td>0</td>
<td>120%</td>
<td>0</td>
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<td>120%</td>
<td>0</td>
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</table>
3. RESULTS

Monte Carlo calculated relative dose rate distributions of the $^{192}$Ir source and shielded $^{153}$Gd source are shown in Figs. 2(a), 2(c), 2(b), and 2(d), respectively. Anisotropy was accounted for in the dose distribution calculations. The MCNP model was benchmarked by comparing the dose rate of a 370 GBq $^{192}$Ir source at a distance of 1 cm from the source calculated from our model with the accepted $^{192}$Ir dose rate in the literature. The results from our model gave an $^{192}$Ir dose rate of $4.246 \times 10^4$ cGy h$^{-1}$ which when compared with the $^{192}$Ir dose rate in the literature$^{28}$ of $4.184 \times 10^4$ cGy h$^{-1}$, indicates a relative difference of less than 1.5%. The same technique for calculating dose rate was used for $^{153}$Gd. The platinum shield reduced the dose rate on the shielded side of the $^{153}$Gd source at 1 cm off-axis to 6.4% of the dose rate on the unshielded side.

Planned conventional HDR-BT and I-RSBT dose distributions for a prostate cancer case are shown in Fig. 3, along with dose difference maps in which the I-RSBT dose is subtracted from the HDR-BT dose. Dose-volume histograms for the urethral gradient margins of 0, 3, and 5 mm are shown in Fig. 4. Plots of the urethral and periapical urethral $D_{0.1cc}$ percentage variation as a function of urethral gradient margin are shown in Fig. 5(a), and the rectum and bladder $D_{1cc}$ percentage variation as a function of urethral gradient margin are shown in Fig. 5(b).

With the increasing values of urethral margin, urethral $D_{0.1cc}$ values and periapical urethral $D_{0.1cc}$ values follow a downward trend. For the case considered, for the same minimum dose to the hottest 98% of the clinical target volume ($D_{98\%}$), I-RSBT reduced urethral $D_{0.1cc}$ below that of conventional HDR-BT by 29%, 33%, 38%, and 44% for urethral dose gradient volumes within 0, 1, 3, and 5 mm of the urethra surface, respectively. Percentages are expressed relative to the prescription dose of 100%. For the same urethral dose gradient volumes, periapical $D_{0.1cc}$ was reduced by 23%, 25%, 28%, and 30%, respectively, rectum $D_{1cc}$ was reduced by 7%, 6%, 6%, and 6%, respectively, and bladder $D_{1cc}$ was reduced by 4%, 5%, 5%, and 6%, respectively. Increasing the urethral margin from 0 to 5 mm for I-RSBT decreased $D_{0.1cc}$ for the urethra and periapical urethra by 16% and 10%, respectively.
FIG. 3. Dose distributions and dose difference maps (I-RSBT dose minus HDR-BT dose) for different urethral margins of $^{192}$Ir based HDR-BT and $^{153}$Gd based I-RSBT sampled onto a CT scan of a prostate cancer patient.

relative to the prescription dose (Fig. 5). The urethral margin of 0 mm was included in the model in order to demonstrate the relative sparing of the urethra without a relaxed prescription dose constraint.

The treatment time (sum of all dwell times) to deliver 20 Gy to the CTV averaged over all urethral margins using HDR-BT with a single 370 GBq $^{192}$Ir source was 12 min. For the case considered, the treatment time (sum of all dwell times) to deliver 20 Gy to the CTV averaged over all urethral margins using I-RSBT with ten 62 GBq $^{153}$Gd sources was 154 min. The treatment times for each urethral margin varied by less than 5% from the average for HDR-BT and I-RSBT.

4. DISCUSSION

The limitations of the lower dose rate of the $^{153}$Gd source relative to that of 370 GBq $^{192}$Ir source can be overcome in clinical application with the use of a multiple catheter system. The current lack of availability of sufficient quantities of $^{153}$Gd required for clinical use of the $^{153}$Gd-based I-RSBT system is a limitation of the proposed system. However, there are currently mass production techniques for $^{153}$Gd in development that could be used to make sufficient quantities of $^{153}$Gd available for BT applications. As proposed, the I-RSBT approach would not have a high enough dose rate to be considered HDR-BT, which would require a dose rate of greater than 12 Gy/h. I-RSBT would be considered medium dose rate brachytherapy, which has a dose rate of between 1 and 12 Gy/h.

The dose difference maps shown in Fig. 3 indicate that I-RSBT substantially reduced the dose to the rectum, but the dose anterior to the prostate and inferior to the bladder, particularly in the pubic arch, is greater for I-RSBT than HDR-BT. The clinical implications of this dose increase are unknown, as data demonstrating complications due to increased pubic arch dose are not available. The dose to the pubic arch
delivered with I-RSBT will be patient-dependent, and further studies with more patients are needed in order to determine the range of expected doses. One potentially effective approach is to include the pubic arch as an avoidance structure in the treatment plan optimization process.

There are several considerations that make a 2–3 h delivery feasible for I-RSBT. First, conventional HDR-BT is often delivered on multiple days in which multiple deliveries are done per day, with a single needle implant. In such cases, it is not infrequent for patients to spend 12 h in the clinic for ultrasound-guided needle implantation, CT scan acquisition, treatment planning, delivery, and wait time between deliveries. HDR-BT patients may have an overnight hospital stay with the needles implanted. With the I-RSBT approach, patients can spend a similar amount of time in the clinic with needles implanted, but a greater percentage of that time would be used for the radiation delivery process. Time spent in the clinic for single-fraction I-RSBT may be more than for conventional single-fraction HDR-BT, but still no longer than conventional multifraction HDR-BT. If complications can be reduced by using the I-RSBT approach, then it may be desirable for patients to undergo such a procedure and spend an additional few hours under treatment. The effects of fractionation in high-dose-rate brachytherapy may provide a therapeutic advantage, and caution should be exercised when defining clinical trials evaluating I-RSBT to ensure that the effectiveness of HDR-BT at controlling disease is not sacrificed for the sake of reducing toxicity. Third, the $^{153}$Gd gamma rays require far less room shielding than $^{192}$Ir gamma rays, and it is possible that patients could be treated in modified procedure rooms rather than in HDR-BT suites, and the concerns regarding facility usage that would accompany a long HDR-BT treatment may not be present with I-RSBT.

Quality assurance will be important for I-RSBT. As the shield-containing catheters are designed to move inside the needles freely, without moving the needles, concerns regarding needle shift during treatment will be the same as those for conventional HDR-BT. The delivery system for I-RSBT has not yet been developed, therefore it is not possible at this time to provide an in-depth explanation of the quality assurance for the I-RSBT system. Justifying the development of a full I-RSBT delivery system, including quality assurance processes, requires establishment of dosimetric and clinical delivery expectations, which is the subject of the current work.

An important consideration when designing the model for I-RSBT was the source design, as variables such as source length and diameter can have a large effect on the resulting...
dose distributions. The 10 mm length of the source was a design decision based on currently clinically utilized sources. Sources with a length of 10 mm have been used previously in Varian VariSource designs modeling the $^{153}$Gd as a 10 mm source was appropriate. The 10 mm source length was chosen, as compared to a shorter source length, because it minimized treatment times for I-RSBT delivery.

An additional parameter considered that can alter treatment times and possibly improve dose distributions was the shield emission angle. Although this concept was not considered in the current work, it is possible that catheters with a number of different shield emission angles could be used during a single I-RSBT delivery. Such an approach could possibly improve healthy tissue sparing without loss of CTV $D_{98\%}$ while reducing treatment time. A similar approach has been considered for intracavitary RSBT and could be extended to I-RSBT. Another approach for decreasing I-RSBT treatment times is to use a combination of $^{192}$Ir and shielded $^{153}$Gd sources. The $^{192}$Ir sources can be used at the periphery of the prostate and the shielded sources could be used close to the urethra. The trade-offs between normal tissue sparing and treatment time using this approach are not yet well understood, however, and require further consideration.

In this treatment planning study, it cannot be claimed that the catheter numbers and arrangements for the HDR-BT and I-RSBT sources are optimal for the sources considered. The positions considered were consistent for both I-RSBT and HDR-BT and they were clinically realistic. Alternative arrangements could be appropriate, and developing an algorithm for determining the optimal catheter positions for I-RSBT is a challenging optimization problem that was beyond the scope of the current work.
The uncertainty associated with the angular position of the source is not yet clear, as it will depend on the I-RSBT delivery method, angular accuracy of any motors involved, and the accuracy with which a feedback-based control system for angular position monitoring can detect and correct for deviations from the intended positions. The dosimetric impact of the positional uncertainty will depend upon optimization technique used to generate the dwell times for each source position and shield angle, as dwell times that are smoothly varying will produce dose distributions that are more robust with respect to positional uncertainties. It is expected that such uncertainties will have the greatest undesirable impact if they cause unexpected cold spots in the prostate or if they cause increases in the dose delivered to the urethra, bladder, and/or rectum than planned, which could result in a worse toxicity than expected.

The rectum and bladder $D_{1cc}$ values for I-RSBT were not reduced relative to HDR-BT as much as the urethral and periapical urethral $D_{1cc}$ values. Rectal dose can be further reduced by injecting hyaluronic acid or SpaceOAR$^\text{TM}$ hydrogel (Augmenix, Inc., Waltham, MA) into the anterior periapical fat, increasing the distance between the rectum and the prostate. Such approaches may be effective if the clinical goal of I-RSBT delivery is to escalate CTV dose under normal tissue constraints, although the bladder dose must still be considered in this process. Reducing the anterior-superior CTV dose to keep bladder dose below the constrained value may be necessary to enable dose escalation that takes full advantage of the urethral sparing benefits of I-RSBT.

In addition to the benefits of the proposed system in patient treatment, the incorporation of proximal and distal platinum caps onto the ends of the shield, shown in Fig. 1(a), enable the catheters to be safely retracted into a shielded container for storage, reducing clinical staff dose due to radiation released along the longitudinal axis of the source.

An alternative source considered for I-RSBT delivery was $^{57}$Co.$^\text{52}$ The advantages of $^{57}$Co over $^{153}$Gd are both a higher specific activity and a slightly longer half-life of 271 days. However, $^{153}$Gd was chosen over the $^{57}$Co source because of its thinner photon tenth-value layer in platinum (0.37 mm for $^{153}$Gd compared to 0.7 mm for $^{57}$Co), which allows a larger source to be used in the same gauge of catheter, and a substantially lower cost per GBq of $^{153}$Gd compared to $^{57}$Co. Because the lower dose rate provided by $^{153}$Gd as a result of its lower specific activity can be overcome by using multiple sources, and the difference in half-lives is unlikely to affect the clinical feasibility of $^{153}$Gd, it was determined that $^{153}$Gd-based system was the preferred source for I-RSBT treatment.$^\text{28}$

5. CONCLUSIONS

The proposed $^{153}$Gd-based I-RSBT system has the potential to reduce urethral and rectal doses relative to conventional techniques. For the case considered, the proposed $^{153}$Gd-based I-RSBT system has the potential to lower the urethral dose relative to HDR-BT by 29%–44% if the clinician allows a urethral dose gradient volume of 0–5 mm around the urethra to receive a dose below the prescription. A multi-source approach is necessary in order to deliver the proposed $^{153}$Gd-based I-RSBT technique in reasonable treatment times.

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