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Scientific Article

Normal Tissue Integral Dose as a Result of Prostate Radiation Therapy: A Quantitative Comparison Between High-Dose-Rate Brachytherapy and Modern External Beam Radiation Therapy Techniques

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Abstract

Purpose: Quantification of integral radiation dose delivered during treatment for prostate cancer is lacking. We performed a comparative quantification of dose to nontarget body tissues delivered via 4 common radiation techniques: conventional volumetric modulated arc therapy, stereotactic body radiation therapy, pencil-beam scanning proton therapy, and high-dose-rate brachytherapy.

Methods and Materials: Plans for each radiation technique were generated for 10 patients with typical anatomy. For brachytherapy plans, virtual needles were placed to achieve standard dosimetry. Standard planning target volume margins or robustness margins were applied as appropriate. A "normal tissue" structure (entire computed tomography simulation volume minus planning target volume) was generated for integral dose computation. Dose-volume histogram parameters for targets and normal structures were tabulated. Normal tissue integral dose was calculated by multiplying normal tissue volume by mean dose.

Results: Normal tissue integral dose was lowest for brachytherapy. Pencil-beam scanning protons, stereotactic body radiation therapy, and brachytherapy resulted in 17%, 57%, and 91% absolute reductions compared with standard volumetric modulated arc therapy, respectively. Mean nontarget tissues receiving 25%, 50%, and 75% of the prescription dose were reduced by 85%, 76%, and 83% for brachytherapy relative to volumetric modulated arc therapy, by 79%, 64%, and 74% relative to stereotactic body radiation therapy, and 73%, 60%, and 81% relative to proton therapy. All reductions observed using brachytherapy were statistically significant.

Conclusions: High-dose-rate brachytherapy is an effective technique for reducing dose to nontarget body tissues relative to volumetric modulated arc therapy, stereotactic body radiation therapy, and pencil-beam scanning proton therapy.

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Introduction

Prostate cancer is the most common noncutaneous cancer in men.[1] Both external beam radiation therapy (EBRT) and high-dose-rate brachytherapy (HDR) are considered standard treatment options for appropriately selected men with localized prostate cancer.[2] In recent years, hypofractionated photon techniques (≥240 cGy per treatment fraction) and proton therapy have seen increased utilization in the definitive management of prostate cancer.[3,4] However, the integral radiation dose delivered to the patient using EBRT techniques is seldom considered when weighing options for prostate radiation therapy (RT) but holds the potential for harm and should be of concern.[5-7] Intuitively, a technique such as brachytherapy that delivers therapeutic radiation dose from within the target itself should be associated with reduced integral radiation dose exposure to the patient. Although prior studies have attempted to quantify differences in volumetric dose parameters between commonly used treatment modalities, data regarding the precise quantification of integral dose reduction that is achieved with brachytherapy relative to photon and proton EBRT techniques are lacking.[8]

Compared with radical prostatectomy, RT for localized prostate cancer has been associated with an increased risk for secondary malignancy (SM), including bladder and rectal cancers.[9-13] However, SM rates are difficult to quantify, largely because of long time intervals between tissue irradiation and SM development, varying definitions of SM timing in the literature, and confounding factors such as tobacco use.[11] Furthermore, the rate of SM may differ for modern conventionally fractionated volumetrically modulated arc therapy (VMAT), stereotactic body RT (SBRT) planned using a VMAT technique, pencil-beam scanning proton therapy (PBS), and HDR brachytherapy compared with historical EBRT techniques.[12] Although several meta-analyses have suggested an increased risk of SM in men treated with EBRT, the association between brachytherapy and SM risk is not as well defined.[13,14]

Different RT modalities can result in widely variable dose distributions. VMAT and SBRT typically generate tight dose gradients at higher isodose levels at the expense of increased tissue exposure to lower doses of radiation. Proton therapy uses the concept of the Bragg peak to deliver highly conformal RT plans with minimal exit dose, thereby decreasing dose to normal tissues beyond the target.[3] In contrast, brachytherapy inherently minimizes dose to surrounding tissues because the radiation source is located within the target itself and is of lower energy, albeit with greater dose heterogeneity within the target. The clinical consequences of large volumes of normal tissue irradiated to low doses using VMAT, SBRT, and to a lesser extent PBS therapy, remain unclear. Given the good clinical outcomes and modest toxicity often associated with early-stage disease, it stands to reason that an effort should be made to expose patients to as little radiation as is therapeutically necessary.

The risk of SM after RT has important implications for treatment selection and patient counseling, and yet the risks associated with specific dose gradients remain poorly defined.[15] The first step in obtaining a better understanding of this risk is to quantify and compare the dose distributions within nontarget tissues for various modern RT techniques. Given brachytherapy's theoretical advantage to spare normal tissues, we sought to quantify the extent to which dose is reduced for HDR plans compared with VMAT, SBRT, and PBS plans.

Methods and Materials

Patients

This study was approved by our hospital's institutional review board. We selected 10 patients previously treated at our institution for whom simulation images and contouring structures were available. All EBRT treatments were delivered using VMAT, a sophisticated form of intensity modulated RT (IMRT) in which radiation is delivered via 1 or more arcs or gantry rotations to maximize dose conformity. To examine the effect of clinical target volume (CTV) size on nontarget body tissue dose, we intentionally selected men with variably sized prostates. Patients who underwent procedures to modify rectal spacing (either by placement of hydrogel rectal spacer or use of a rectal balloon) were excluded. To assess the effect of prostate volume on normal tissue dose, only patients who had undergone combined computed tomography/magnetic resonance imaging simulation were selected. Contours that had been generated for the patient's actual treatment, including contours of the prostate, seminal vesicles, rectum, bladder, and whole body, were reviewed for accuracy and used without modification for these analyses. For purposes of this study, the whole-body volume was defined as the volume of normal tissue from the level of the inferior pole of the kidneys to the proximal one-third of the femurs.

EBRT target delineation

Standardized CTVs consisted of the prostate and proximal 1 cm of seminal vesicles. The same CTV was used for all 4 treatment modalities. Standardized planning target volume (PTV) expansions for the photon EBRT plans included a 0.7-cm expansion limited to 0.5 cm posteriorly for traditional VMAT and a uniform 0.3-cm circumferential expansion for SBRT. Robustness optimization for PBS planning used a 0.5 cm patient position uncertainty

margin and 3.5% range uncertainty. The treatment planning system used 26 standard potential dose perturbations, which were accounted for in the robustness calculations. A "normal tissue" structure was generated by subtracting the CTV from the whole-body contour. Urethral contours were generated using a standard 6-mm diameter ring for all patients, in line with our clinical practice for HDR.

HDR target delineation

HDR treatment plans were generated using the same CTV and normal tissue contours as for EBRT treatment planning. No PTV margin was applied for HDR patients, per standard practice. Virtual needles were placed on the planning computed tomography images using typical implant geometry to achieve acceptable HDR dosimetry within typical dose parameters. The median number of virtual needles necessary to achieve acceptable implant geometry was 19 (range, 16-22).

Dose planning

VMAT, SBRT, PBS, and HDR plans were generated consistent with in-house standards for target coverage and critical structure dose constraints (Table E1). Prescription dose and fractionation was 7000 cGy in 28 fractions for VMAT, 7000 cGy (relative biological effectiveness) in 28 fractions for PBS, 3625 cGy in 5 fractions for SBRT, and 2700 cGy in 2 fractions for HDR. For VMAT and SBRT plans, ≥98% of the PTV was to receive the prescription dose. For PBS plans, ≥98% of the CTV was to receive the prescription dose. For HDR plans, ≥95% of the CTV was to receive the prescription dose, along with 100% of the CTV receiving 95% of the prescription dose. For heterogeneity objectives, a maximum volume of 0.03 cc of the PTV was to receive a dose ≤105% of the prescription dose for VMAT and SBRT plans, a maximum volume of 0.03 cc of the CTV was to receive ≤105% of the prescription dose for PBS plans, and <60% and <30% of the target volume was to receive 125% and 150% of the prescription dose, respectively, for HDR plans. Some flexibility was applied to HDR planning goals/constraints given that external beam imaging was used for HDR planning (ie, suboptimal patient selection and positioning for HDR planning was inherent).

Because the absolute prescription dose varied for each modality, we report the volumes, measured in cubic centimeters (cc) of organs at risk receiving relative doses (expressed as a percent of the prescription dose) for each modality. This allowed a more direct comparison of the dose to which each organ was exposed for various plans. VMAT and SBRT planning was performed using Pinnacle version 16.2 (Phillips North America LLC, Cambridge, MA), PBS planning was performed using RayStation 6.0 (RaySearch Laboratories AB, Stockholm, Sweden), and HDR planning was performed using Oncentra version 4.2.3 (Elekta AB, Stockholm, Sweden).

Analysis and statistics

Relative and absolute dose-volume histogram parameters were collected for each plan. To compare the overall difference in normal tissue dose for each treatment modality, normal tissue integral dose (NTID) was calculated by multiplying the normal (nontarget) tissue volume (expressed in L) by mean relative dose (expressed in Gy).[16] Statistical analysis was performed using Excel (Microsoft Corporation, Redmond, WA) and RStudio, version 1.2.5033 (RStudio PBC, Boston, MA). Normality of each distribution was assessed using the Shapiro-Wilk test, and means were compared using the Mann-Whitney *U* test because of the small sample size precluding the assumption of a normal distribution.

Results

Median patient age was 66.5 years (range, 53-77). CTVs, defined on simulation magnetic resonance images, ranged from 27 to 161 cc. Four patients had National Comprehensive Cancer Network intermediate-risk disease and 6 had high-risk disease.[2] Median Gleason score was 7 (range, 6-9), and median pretreatment prostate-specific antigen was 5.7 ng/mL (0.6-16.0). Of the 10 representative patients used for our analyses, 4 had been treated with VMAT and 6 with VMAT plus HDR boost. With a minimum follow-up of 2 years, no patients had failed treatment at the time of this analysis.

The median CTV measured 61 cc (range, 27-161 cc). Median PTV volumes for VMAT and SBRT were 169 cc (range, 85-326 cc) and 116 cc (range, 52-240 cc), respectively. Treatment planning parameters were met or considered within variation acceptable by the authors. Actual target dose volume parameters are shown in Table 1.

Dose volume parameters for the bladder, rectum, and urethra are shown in Table 2. Doses to these organs were within what are considered standard constraints. In general, volumes of bladder and rectum receiving 75% to 99% of the prescription dose (V75-V99) were lower for PBS plans compared with VMAT/SBRT plans, but were lowest for HDR plans. The urethra V105-V115 was higher for HDR plans compared with VMAT, SBRT, and PBS plans.

Nontarget body tissue doses and NTIDs are shown in Table 3. Compared with VMAT and SBRT, HDR resulted in statistically significant decreases in the mean nontarget tissue at all examined dose levels (V10 through V75). Reductions in nontarget dose seen with HDR were

Table 1 PTV and CTV coverage

V% (mean)	VMAT (range)	SBRT (range)	PBS (range)	HDR (range)
V95	100.0% (100.0%-100.0%)	100.0% (100.0%- 100.0%)	100.0% (99.9%-100.0%)	99.2% (98.3%-99.7%)
V98	99.8% (99.6%-99.9%)	99.7% (99.6%-99.9%)	100.0% (99.9%-100.0%)	98.4% (97.1%-99.3%)
V100	98.0% (98.0%-98.2%)	98.0% (98.0%-98.2%)	98.3% (97.9%-99.5%)	97.6% (96.0%-98.8%)
V105	0.0% (0.0%-0.0%)	0.0% (0.0%-0.0%)	0.0% (0.0%-0.0%)	93.1% (90.7%-94.9%)
V110	0.0% (0.0%-0.0%)	0.0% (0.0%-0.0%)	0.0% (0.0%-0.0%)	84.8% (81.2%-87.0%)
V125	0.0% (0.0%-0.0%)	0.0% (0.0%-0.0%)	0.0% (0.0%-0.0%)	56.2% (52.2%-59.7%)
V150	0.0% (0.0%-0.0%)	0.0% (0.0%-0.0%)	0.0% (0.0%-0.0%)	25.9% (22.1%-30.4%)

Abbreviations: CTV = clinical target volume; HDR = high-dose-rate brachytherapy; PBS = pencil-beam scanning proton therapy; PTV = planning target volume; SBRT = stereotactic body radiation therapy; VMAT = volumetrically modulated arc therapy.

Table 2 Relative dose to organs at risk

	VMAT (range)	SBRT (range)	PBS (range)	HDR (range)
Bladder (mean)				
V100	13.0 cc (5.0-21.1)	4.7 cc (1.3-8.4)	6.1 cc (0.3-15.6)	0.2 cc (0.0-0.7)
V95	17.9 cc (8.0-21.1)	8.2 cc (3.3-14.5)	9.9 cc (1.7-20.7)	0.2 cc (0.0-0.7)
V90	21.5 cc (10.5-31.8)	10.8 cc (4.9-17.9)	13.0 cc (3.3-25.6)	0.7 cc (0.0-1.9)
V85	24.6 cc (12.7-35.7)	13.2 cc (6.5-21.3)	15.1 cc (4.2-29.4)	1.3 cc (0.1-3.1)
V75	30.9 cc (15.6-44.0)	18.1 cc (9.3-29.0)	19.9 cc (3.4-35.9)	3.4 cc (0.8-6.8)
Rectum (mean)				
V100	3.2 cc (1.1-6.2)	0.7 cc (0.2-1.1)	0.8 cc (0.0-2.0)	0.0 cc (0.0-0.0)
V95	5.4 cc (2.1-9.4)	2.1 cc (0.7-3.5)	2.7 cc (0.4-3.8)	0.0 cc (0.0-0.0)
V90	7.2 cc (3.0-11.7)	3.4 cc (1.3-5.3)	4.5 cc (1.0-6.4)	0.0 cc (0.0-0.1)
V80	10.5 cc (4.8-15.2)	6.1 cc (2.6-8.7)	7.4 cc (1.9-12.2)	0.4 cc (0.0-1.2)
V75	12.3 cc (6.0-17.0)	7.6 cc (7.7-11.3)	9.0 cc (2.3-14.6)	1.2 cc (0.2-2.5)
Urethra (mean)				
V105	0.0 cc (0.0-0.0)	0.0 cc (0.0-0.0)	0.0 cc (0.0-0.0)	4.8 cc (0.3-44.4)
V110	0.0 cc (0.0-0.0)	0.0 cc (0.0-0.0)	0.0 cc (0.0-0.0)	0.0 cc (0.0-2.6)
V115	0.0 cc (0.0-0.0)	0.0 cc (0.0-0.0)	0.0 cc (0.0-0.0)	0.0 cc (0.0-0.0)

Abbreviations: HDR = high-dose-rate brachytherapy; PBS = pencil-beam scanning proton therapy; SBRT = stereotactic body radiation therapy; VMAT = volumetrically modulated arc therapy.

generally most pronounced at lower dose levels. The mean absolute reduction was largest for V10 (absolute volume reductions of 4315 cc [$P < .001$] and 3680 cc [$P < .001$] compared with VMAT and SBRT, respectively) and smallest for V75 (absolute volume reductions of 197 cc [$P < .001$] and 112 cc [$P < .001$], respectively). Compared with PBS, HDR resulted in statistically significant decreases in the mean nontarget tissue for all dose levels except V10% (ie, V20 through V75). For HDR versus PBS, the mean absolute reduction was largest for V25 (absolute volume reduction of 1151 cc [$P < .001$]) and smallest for V75 (absolute volume reduction of 170 cc [$P < .001$]).

Comparing VMAT and SBRT against PBS, there was a statistically significant decrease for most parameters when comparing PBS versus VMAT, and a statistically significant difference in V10, V20, and V75 for PBS versus SBRT.

When VMAT and SBRT were compared, there were smaller absolute changes that were significant for some parameters, with absolute differences in volume ranging from 85 to 635 cc. Differences in mean V10 and V50 were not significant. Coverage of the prescription isodose region, V100, was also not significantly different between the modalities.

Cumulative differences in nontarget tissue doses were quantified using NTID. The NTID values for VMAT,

Table 3 Nontarget body tissue doses and NTID

V% (mean)	VMAT (range)	SBRT (range)	HDR (range)	PBS (range)
V10	6063 cc (4367-9550)	5428 cc (3853-8703)	1748 cc (806- 3464)*,†	2036 cc (1468-3030) ‡,§
V20	4014 cc (2541-7029)	3154 cc (1637-143) ‖	607 cc (265-263)*,†, ¶	1717 cc (1220-2591) ‡,§
V25	2810 cc (1467-5302)	2047 cc (907-4501) ‖	431 cc (189-901)*,†, ¶	1582 cc (1119- 2393) ‡
V30	1855 cc (932-3688)	1294 cc (584-2917) ‖	321 cc (143-679)*,†, ¶	1423 cc (988-2181)
V40	896 cc (483-1688)	623 cc (305-1251)	199 cc (88-418)*,†, ¶	522 cc (333-913) ‡
V50	539 cc (299-963)	371 cc (187-719) ‖	132 cc (60-282) *,†,¶	327 cc (229-493) ‡
V55	440 cc (247-775)	300 cc (154-572) ‖	109 cc (50-236) *,†,¶	298 cc (205-454) ‡
V60	368 cc (208-641)	248 cc (129-465) ‖	91 cc (41-197)*,†, ¶	273 cc (187-417) ‡
V75	237 cc (137-408)	152 cc (81-277) ‖	40 cc (0-111)*,†, ¶	210 cc (122-298) §
NTID (L· Gy)	143 (67-242)	118 (53-208) ‖	12 (4.7-22)*,†, ‡	61 (27-129) ‡,§

Abbreviations: HDR = high-dose-rate brachytherapy; NTID = normal tissue integral dose; PBS = pencil-beam scanning proton therapy; SBRT = stereotactic body radiation therapy; VMAT = volumetrically modulated arc therapy.

* $P < .05$ for HDR vs VMAT.

† $P < .05$ for HDR vs SBRT.

‡ $P < .05$ for PBS vs VMAT.

§ $P < .05$ for PBS vs SBRT.

‖ $P < .05$ for SBRT vs VMAT.

¶ $P < .05$ for HDR vs PBS.

NTID is the product of mean relative dose and normal tissue volume.

SBRT, PBS, and HDR were 143 L · Gy (67-242), 118 L · Gy (53-208), 61 L · Gy (27-129), and 12 L · Gy (4.7-22), respectively. The mean NTID for PBS was significantly lower than that of VMAT and SBRT ($P < .001$). Furthermore, the NTID for HDR was significantly lower than that of VMAT, SBRT, and PBS ($P < .001$). Finally, the NTID for SBRT was also significantly lower than that of VMAT ($P = .03$).

Relative differences in nontarget body tissue dose parameters are shown in Fig. 1. SBRT resulted in modest

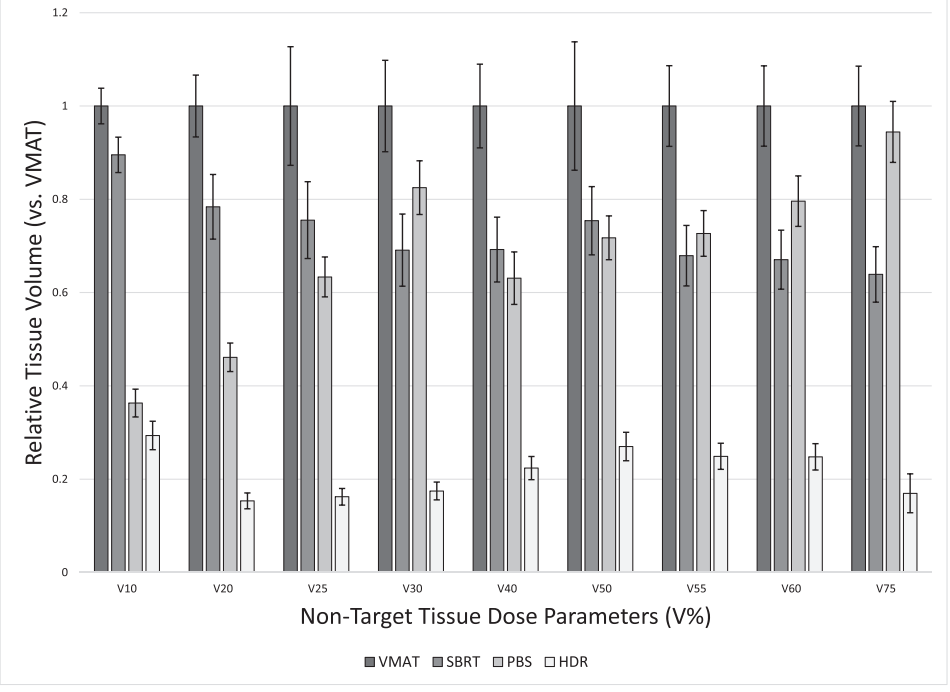

Figure 1 Nontarget tissue doses relative to volumetrically modulated arc therapy (VMAT). Error bars represent standard error of the mean (SEM).

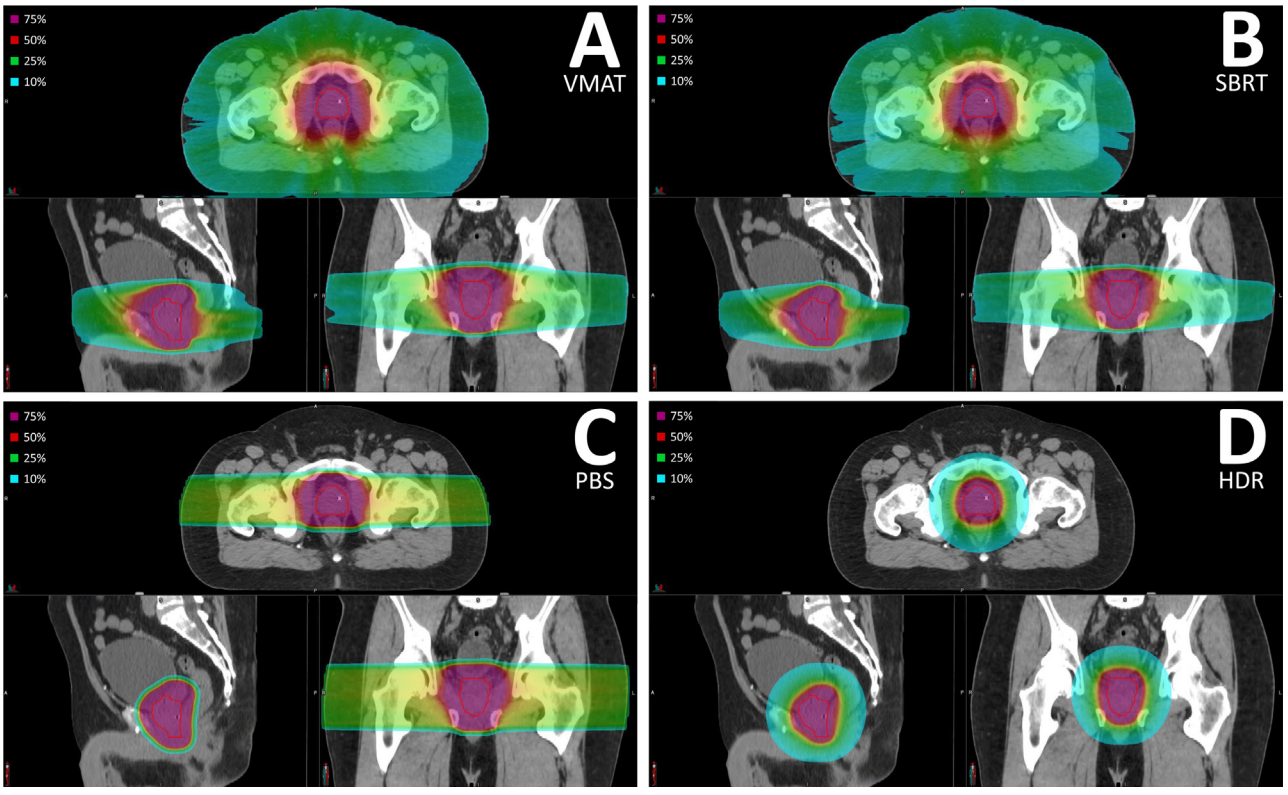

Figure 2 Dose distribution for (A) volumetrically modulated arc therapy (VMAT) plans, (B) stereotactic body radiation therapy (SBRT) plans, (C) pencil-beam scanning proton therapy (PBS), and (D) high-dose-rate brachytherapy (HDR) plans. Doses of 75% of the prescription dose are shown in red, 50% in orange, 25% in green, and 10% in blue. The red contour represents the planning clinical target volume (CTV).

reductions relative to VMAT (ranging from 10%-36% for dose levels ranging from V10-V75). PBS resulted in more notable reductions relative to VMAT, ranging from 6% to 64%. Relative reductions seen in comparing HDR to VMAT, SBRT, and PBS ranged from 71% to 85%, 63% to 80%, and 19% to 82%, respectively. Representative isodose distributions for VMAT, SBRT, PBS, and HDR plans are shown in Fig. 2.

Discussion

To our knowledge, this is the first study to directly quantify normal tissue integral radiation dose between each of the most commonly used and emerging prostate cancer RT techniques. HDR results in a substantial reduction in nontarget body tissue dose relative to VMAT, SBRT, and PBS plans. HDR was found to reduce NTID by approximately 90% compared with both VMAT and SBRT plans and 80% for PBS plans. In contrast, the overall reduction in NTID for SBRT versus VMAT was approximately 17%, and reductions in dosimetric parameters such as V10%, V20%, and so forth, were only statistically significant at specific dose levels. PBS plans resulted in a mean NTID reduction of 58% and 49% compared with VMAT and SBRT, respectively.

Quality of life profiles after IMRT, SBRT, PBS, and HDR brachytherapy are generally considered similar to one another.[17] EBRT results in low rates of serious genitourinary and gastrointestinal toxicities, which may be slightly more frequent after moderate hypofractionation.[18,19] Although long-term toxicity data for SBRT continue to mature, to date it has been shown to have low rates of high-grade late toxicities and modest, transient declines in urinary and bowel quality of life.[20,21] In comparison to photon-EBRT, PBS therapy for prostate cancer is associated with decreased dose to nearby normal structures, though the clinical benefit of this dose reduction is uncertain.[3,22,23] HDR monotherapy has been shown to have acceptable rates of toxicity that are comparable to other modalities, with a general trend of modestly increased acute urinary symptoms and fewer bowel symptoms.[24,25]

Overall, existing data do not clearly favor VMAT, SBRT, PBS, or HDR in terms of toxicity. However, it stands to reason large reductions in the doses to normal tissues at risk for complications may translate to reductions in toxicity. This is the primary argument in favor of proton therapy, which is currently being evaluated in the COMPPARE study (A Prospective Comparative Study of

Outcomes with Proton and Photon Radiation in Prostate Cancer; NCT03561220). A previous dose distribution study comparing proton therapy to IMRT estimated that protons reduce the volume of rectum receiving 100% and 90% of the prescription dose by 42% and 44%, respectively.[23] Similarly, prior work by Georg et al[8] demonstrated statistically significant decreases in dose to the urethra, rectal wall, and bladder wall for both HDR and PBS with respect to VMAT. By comparison, in the current analysis, mean rectal V100 and V90 were both 0 cc for HDR treatment plans − a 100% relative dose reduction compared with VMAT, SBRT, and PBS for these same parameters. Therefore, it could be argued that HDR should result in an even more substantial reduction in the rate of rectal toxicity than proton therapy, and recently published retrospective evidence has suggested just that.[26]

Given prostate cancer's favorable prognosis, the risk of secondary cancer development is an important consideration, especially for younger patients. Men who receive RT for treatment of prostate cancer are at increased risk of developing secondary cancers, and there is evidence that the risk of SM is lower after brachytherapy compared with EBRT.[9-13] In addition, brachytherapy is more commonly used in younger, healthier men.[13] Furthermore, the risk of SM is affected by the type of normal tissue exposed to dose.[27] Therefore, further studies of SM risks as a function of dose gradient and tissue type are needed.[15] Correlation and quantification of whole-body dose exposure, as outlined in this paper, is an important initial step in this process.

Because RT-mediated carcinogenesis exhibits a linear dose-response relationship, the normal tissues at highest risk for SM are those that receive higher doses (ie, the rectum and bladder, which are immediately adjacent to the target).[27-30] Because HDR results in a steeper dose falloff outside the target, it should result in a lower risk of SM for these tissues. Although other studies have attempted to demonstrate this via methods such as Schneider's organ equivalent dose modeling, real-world integral dose and SM risk data are lacking.[31] Additionally, even tissues exposed to relatively lower doses of radiation, including more distal areas of bladder and rectum, soft tissues, and skin, should be at reduced risk of SM if the dose can be reduced, even if the absolute risk for these tissues is small. With IMRT and VMAT, larger volumes of normal tissue are exposed to low doses of radiation, and it has been estimated that this conveys a theoretical 0.5% absolute increase in the risk of SM.[28]

A link between the reduced normal tissue doses that can be achieved with brachytherapy and a decreased risk of SM has been shown for breast cancer.[32] Breast planning studies have demonstrated significantly lower doses to adjacent tissues for brachytherapy plans compared with EBRT plans, and the risk of contralateral breast cancer development is 2.5-fold greater after exposure to even low doses of radiation.[33-36]

When we compared HDR, SBRT, VMAT, and PBS plans for individual patients with respect to CTV size (target volume size), we saw that for each RT modality, larger CTVs resulted in higher NTID values (a single parameter representing overall normal tissue dose). Additionally, our analyses did not include anticipated secondary dose from the treatment machines. However, HDR still achieved the lowest NTID for each individual patient. HDR has, in fact, been shown to be equally effective and well tolerated when used for appropriately selected men with large prostates (60 cc or greater in size) compared with men with smaller prostate glands.[37,38] Therefore, the ability of HDR to reduce normal tissue dose may have more important implications in this regard for toxicity and SM risk for men with large prostate glands who remain candidates functionally and anatomically to receive HDR treatment.

Conclusion

High-dose-rate brachytherapy for prostate cancer is associated with substantial reductions in normal tissue integral radiation dose exposure relative to VMAT, SBRT, and PBS techniques. Given prostate cancer's generally favorable prognosis, assessment of toxicity profiles and SM risk is a critical consideration. However, EBRT techniques do result in excellent clinical outcomes for men with localized prostate cancer, and many patients are not good brachytherapy candidates. Decisions as to the suitability of a given patient for brachytherapy based on general health status, pelvic anatomy, urinary function, and so forth, are critical. For patients who are suitable brachytherapy candidates, the dose reductions achievable with HDR relative to VMAT, SBRT, and PBS are substantial and should be an important factor in the decision-making process when considering treatment options for localized prostate cancer.

Supplementary materials

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.adro.2022.101160.

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