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Dosimetric analysis of testicular doses in prostate intensity-modulated and volumetric-modulated arc radiation therapy at different energy levels

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ABSTRACT

The aim of this study is to evaluate the incidental testicular doses during prostate radiation therapy with intensity-modulated radiotherapy (IMRT) and volumetric-modulated arc radiotherapy (VMAT) at different energies. Dosimetric data of 15 patients with intermediate-risk prostate cancer who were treated with radiotherapy were analyzed. The prescribed dose was 78 Gy in 39 fractions. Dosimetric analysis compared testicular doses generated by 7-field intensity-modulated radiotherapy and volumetric-modulated arc radiotherapy with a single arc at 6, 10, and 15 MV energy levels. Testicular doses calculated from the treatment planning system and doses measured from the detectors were analyzed. Mean testicular doses from the intensity-modulated radiotherapy and volumetric-modulated arc radiotherapy per fraction calculated in the treatment planning system were 16.3 ± 10.3 cGy *vs* 21.5 ± 11.2 cGy ($p = 0.03$) at 6 MV, 13.4 ± 10.4 cGy *vs* 17.8 ± 10.7 cGy ($p = 0.04$) at 10 MV, and 10.6 ± 8.5 cGy *vs* 14.5 ± 8.6 cGy ($p = 0.03$) at 15 MV, respectively. Mean scattered testicular doses in the phantom measurements were 99.5 ± 17.2 cGy, 118.7 ± 16.4 cGy, and 193.9 ± 14.5 cGy at 6, 10, and 15 MV, respectively, in the intensity-modulated radiotherapy plans. In the volumetric-modulated arc radiotherapy plans, corresponding testicular doses per course were 90.4 ± 16.3 cGy, 103.6 ± 16.4 cGy, and 139.3 ± 14.6 cGy at 6, 10, and 15 MV, respectively. In conclusions, this study was the first to measure the incidental testicular doses by intensity-modulated radiotherapy and volumetric-modulated arc radiotherapy plans at different energy levels during prostate-only irradiation. Higher photon energy and volumetric-modulated arc radiotherapy plans resulted in higher incidental testicular doses compared with lower photon energy and intensity-modulated radiotherapy plans.

Introduction

Radiotherapy (RT) is an important treatment strategy for prostate cancer, which provides proven improved tumor control by dose escalation.[1,2] Techniques such as volumetric-modulated arc therapy (VMAT) and intensity-modulated RT (IMRT) are able to generate conformal isodoses that significantly limit the exposure of organs at risk, and reduce normal tissue toxicity.[3,4] Most studies have focused on femur, rectum, and bladder doses. However, incidental doses to the testes during prostate RT could lead to impaired endocrine function of Leydig cells.[5] Besides the systemic effects of hypogonadism, such as lack of libido, erectile dysfunction, flushing, muscle atrophy, and increased risk of cardiac events, iatrogenic hypogonadism has confounding effects on prostate-specific antigen after RT.[6-9] This is particularly significant for techniques that potentially deliver higher scattered testicular doses, such as whole-pelvic RT, and higher doses of radiation such as those used in dose-escalation trials.[6,10] There have been a few clinical studies demonstrating that even modest doses in the range of 2 to 4 Gy can result in significant long-term hormonal changes.[7,11]

Although IMRT is commonly used to treat prostate cancer, the potential downside of IMRT is increased RT delivery time, which results in a greater integral body dose that might increase undesirable exposure of normal tissue to low doses of radiation. VMAT is an innovative form of IMRT optimized to allow the radiation dose to be efficiently delivered using a dynamic

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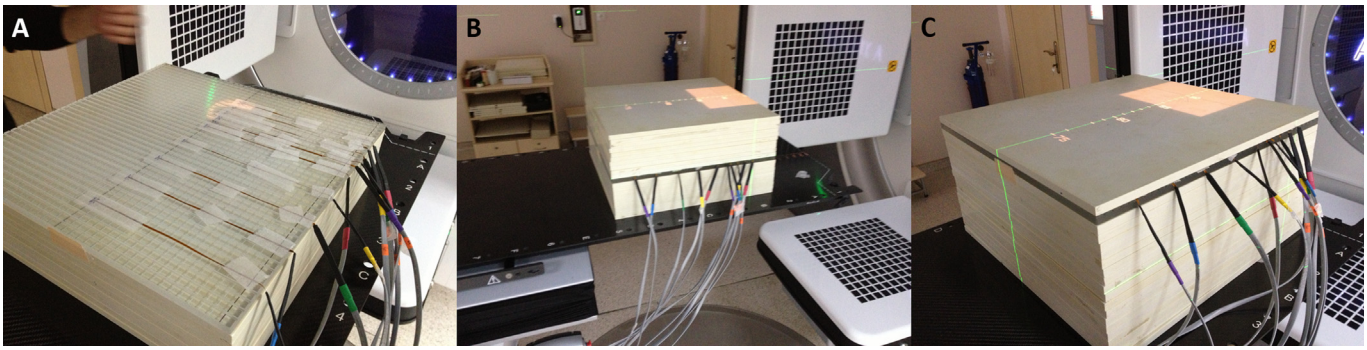

Fig. 1. (A) The MOSFET detectors were placed within the plate phantom from the center of the irradiated field to 30 cm with 2-cm distance. (B) The MOSFET detectors were placed at a 10-cm depth, sandwiched between the solid phantom plates, and irradiated with the prescribed dose. (C) For scattered doses, the MOSFET detectors were placed at 1-cm depth and irradiated. (Color version of figure is available online.)

modulated arc. The VMAT simultaneously coordinates gantry rotation, multileaf collimator (MLC) motion, and dose rate modulation, which facilitates highly conformal RT.[4,12]

There have been a few dosimetric studies evaluating incidental testicular irradiation, which have been based mostly on large field irradiation.[6,10] However, incidental testicular irradiation during VMAT and IMRT at different energy levels has not been well studied. Recently, Martin *et al.*[13] compared mean testicular doses delivered by VMAT or IMRT, and they found that mean testicular dose was higher in VMAT plans compared with IMRT plans. The aim of the present study was to compare incidental testicular doses under VMAT and 7-field IMRT protocols with dynamic MLCs using the Monte Carlo algorithm treatment planning system (TPS). The effect of 3 different photon energy levels on testicular doses was also evaluated. For validating the accuracy of the TPS, *in vivo* dosimetric measurements were performed using metal-oxide-semiconductor field-effect transistor (MOSFET) detectors.

Materials and methods

This study included 15 intermediate-risk patients treated for prostate cancer at our institution. All patients had undergone 2.5-mm slice thickness-computed tomography (CT) with a comfortably full bladder and empty rectum. Clinical target volume (CTV) included the prostate and the entire seminal vesicles. The planning target volume (PTV) was defined as CTV with a margin of 6 mm posterior and 10 mm in other directions.[14,15] The organs at risk included the rectum, sigmoid colon, bladder, and femoral heads. Additionally, the testes were contoured by the same physician on the original treatment planning CT scans.

Treatment plans

For all patients, the prescribed dose was 78 Gy delivered in 39 fractions. All plans were normalized to deliver 99% of the prescribed dose to CTV and 95% of the prescribed dose to PTV, which has been described before.[4] The treatment plans were generated using IMRT and VMAT techniques at 6, 10, and 15 MV energies, delivered with an Elekta Axesse linear accelerator. The IMRT plans consisted of seven coplanar fields at gantry angles of 0°, 37°, 75°, 135°, 225°, 285°, and 327°. The plans were calculated with Elekta's Monaco TPS (Elekta, Crawley, UK) using the Monte Carlo algorithm and a sliding window MLC delivery technique. The VMAT plans consisted of a single 360° arc. Gantry speed, MLC leaf position, and dose rate varied continuously during VMAT delivery.[16] All treatment plans were performed for delivery with Axesse linear accelerator (Elekta AB, Stockholm, Sweden). All plans met the same criteria for the PTV and organs-at-risk dose constraints, and were clinically acceptable for treatment delivery. The mean distance between the prostate and testes was measured on TPS by drawing a straight line between the midpoints of the 2 organs. The testicular doses were determined on TPS for all patients.

Dose verification with metal-oxide-semiconductor field-effect transistor detectors

The TPS-predicted data were verified with the doses measured with MOSFET detectors (TN-1002-RDH; Best Medical Canada, Ottawa, Canada) at different energy levels. The planning CT of the phantom plates was taken, and planning was performed for IMRT and VMAT at different energy levels. Doses were measured from the center of the plate phantom to 30 cm with 2 cm distances in the TPS. After generating the treatment plan, the MOSFET detectors were placed within the plate phantom, from the center of the irradiated field to 30 cm with 2 cm distances (Fig. 1A). The MOSFET detectors were put into the MOSFET calibration jig, which was placed at a 10-cm depth, sandwiched between the solid phantom plates, and irradiated with the prescribed dose (Fig. 1B). Additionally, MOSFET detectors were placed at 1 cm depth for assessing superficial scattered doses (Fig. 1C). The scattered doses were calculated outside the irradiated area. The MOSFET reading was performed from the center of the field to 30 cm at consecutive 2 cm distances. All data derived from TPS with the IMRT and VMAT plans at different energy levels were compared with the MOSFET detector findings at depths of 1 cm and 10 cm. To minimize the energy dependence of MOSFET detectors, calibrations for different energy levels were performed.[17]

Statistical analysis

Statistical analysis was performed using SPSS 20.0 (SPSS, Chicago, IL), software. The testicular doses of 15 patients were calculated for the IMRT and VMAT plans at 6, 10, and 15 MV photon energy levels. The testicular doses were compared between the IMRT and VMAT plans at each energy level. A second comparison was performed between photon energies. Wilcoxon's matched-pairs test was applied to determine statistical differences between doses in the IMRT plans *vs* VMAT plans for each energy level. All p values reported were two-sided and $p < 0.05$ was considered significant.

Results

TPS measurements

The mean distance between the center of the prostate and the center of the testes was 13.6 ± 1.4 cm. Maximum and mean testicular doses determined on TPS in 39 fractions are shown in Table 1. Although there were no significant differences in maximum testicular doses between the IMRT and VMAT plans, the calculated mean testicular doses were significantly higher in the VMAT plans compared to the IMRT plans at each energy level. In addition, in the TPS, the testicular doses were significantly decreased with the IMRT and VMAT plans at different energy

Table 1
Mean and maximum testicular doses calculated in the treatment planning system according to radiotherapy technique at 6, 10, and 15 MV energy levels

Energy	IMRT (cGy)	VMAT (cGy)	p
D_{max}			
6 MV	49.6 ± 39.4	49.7 ± 38.8	0.98
10 MV	39.9 ± 30.3	43.6 ± 38.6	0.27
15 MV	34.1 ± 28.2	37.7 ± 26.7	0.21
D_{mean}			
6 MV	16.3 ± 10.3	21.5 ± 11.2	0.03
10 MV	13.4 ± 10.4	17.8 ± 10.7	0.04
15 MV	10.6 ± 8.5	14.5 ± 8.6	0.03

IMRT = intensity-modulated radiotherapy, VMAT = volumetric-arc radiotherapy.