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Research article

Intensity-modulated radiotherapy for whole pelvis irradiation in prostate cancer: A dosimetric and plan robustness study between photons and protons

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ABSTRACT

Purpose: To evaluate the dosimetric impact and plan robustness of using Pencil Beam Scanning (PBS) in patients that requires prophylactic pelvic lymph nodes (PLNs) irradiation for prostate cancer.
Material and methods: Five intermediate to high-risk prostate patients previously treated using volumetric modulated arc therapy (VMAT), were selected for this study. Comparative proton radiotherapy plans were generated, where a three-field intensity modulated proton therapy (IMPT) plan was for the phase 1 planning target volume (PTV1) with PLNs. A technique with two posterior oblique fields using single field uniform dose (SFUD) was used for phase 2 (PTV2) volume, that comprises of the prostate and proximal seminal vesicles (Pro + proxSVs). Plan evaluation was performed on PTV coverage and dose to the organs at risk (OARs) using VMAT plans as a baseline (BL). Robust analysis on clinical target volume (CTV) coverage for the PBS plans was simulated with a 3 and 5 mm setup errors and a 3.5% range uncertainty.
Results: For target coverage, PTV1 and PTV2 showed negligible differences with a comparable homogeneity index (HI) values for both modalities. Proton plans produced a statistically significant lower mean dose to the bladder (32.5 Gy(RBE) vs. 46.5 Gy) and rectum (33.6 Gy(RBE) vs. 42.7 Gy). Dose to the bladder and rectum was equivalent at the high dose region. For the bowel cavity, the mean dose for proton plans were 45% lower compared to VMAT plans. Similarly, proton plans were able to achieve an overall reduction in integral dose for both treatment phase. CTV coverage remained high with all the simulated setup and range errors.
Conclusions: Proposed beam geometries for PTV1 and PTV2 proton plans presented good treatment accuracy with similar target coverage as the VMAT plans. Better sparing of OARs was achieved at the low-medium dose region for the proton plans.

Introduction

The use of external beam radiation therapy (EBRT) is a common treatment approach in the management of intermediate to high-risk prostate cancer [1,2]. Routinely, a volumetric modulated arc therapy (VMAT) technique is used for prostate with prophylactic pelvic lymph nodes (PLNs) irradiation, as it is able to achieve superior target coverage with good organs at risk (OARs) sparing. Early clinical studies reported an acceptable rates of acute grade 2 gastrointestinal (GI) and genitourinary (GU) toxicities with VMAT technique [2,3].

As technology advances in the field of proton beam therapy (PBT), there has been a paradigm shifts from the passive scatter technique to an active or pencil beam scanning (PBS) technique, which allows a steeper dose gradient to be achieved with very little dose to the distal region of the target [4]. There are further subdivisions in the PBS techniques, namely single field uniform dose (SFUD) or intensity modulated proton therapy (IMPT).

In SFUD, all spots are optimized independently such that each proton beam provides a homogeneous target coverage [5]. Parallel-opposed SFUD technique is commonly used in prostate alone planning whereby it is able to decrease low-medium dose

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to the bladder and rectum, with significant reduction in low dose bath to the surrounding healthy tissues when compared with VMAT as demonstrated in several studies [6,7]. Although SFUD is less sensitive to setup errors and beam range uncertainty, this optimization method is not suitable in geometrically challenging targets such as whole pelvic radiotherapy (WPRT). The dose distribution is less conformal to the target, with edges of high dose within normal healthy tissues [8]. Sparing of proximal OARs such as the bowels, bladder and rectum is inferior compared to using VMAT.

In IMPT, spots from all proton beams are optimized simultaneously in such a way that each field individually delivers an inhomogeneous dose but when the dose from all fields is summed up, the plan delivers a homogeneous dose across the target volume. This allows us to deliver plans with superior target coverage and/or OARs sparing due to additional modulation possible within the target, like what we achieve in photon-based inverse planning techniques [9]. On the downside, the steep dose gradients within the target increases the susceptibility of IMPT to setup and range errors [10]. There is a great potential of using IMPT to treat concave targets such as WPRT for prostate cancer if a planning method can be devised to overcome the disadvantage of being highly sensitive to uncertainties.

Split target technique using IMPT has been used to treat small complex targets to the thoracic region [11]. The application of this method in large complex volume using the proposed beam geometry in WPRT has not been widely studied. The aim of this pilot study is to propose a technique using IMPT in phase 1 planning that involves a complicated target and SFUD for phase 2 planning in view of the target simplicity. A dosimetric comparison in terms of target coverage and dose to OARs will be carried out using plans generated with VMAT as baseline (BL). Plan robustness test of the proposed beam geometry in the event of patient setup error and range uncertainty will be analyzed for clinical target volume (CTV) coverage.

Material and methods

Institutional review committee approval was obtained for this retrospective dosimetric study. This pilot study included five intermediate to high-risk prostate patients with PLNs irradiation.

Simulation

All prostate cancer patients underwent a computed tomography (CT) simulation on a GE Lightspeed RT16 CT scanner (GE Healthcare, Chicago, Illinois, US) in a supine position with arms on the chest, using a0.25 slice thickness. A leg immobiliser was used for stabilisation and reproducibility. As per institutional protocol, a comfortably full bladder was achieved by requesting patients to first empty their bladder and then drink 2 cups of water (400 ml) 30 min prior to the CT simulation scan. The same protocol was continued for each radiotherapy treatment session. No specific rectal preparation protocol was enforced, but all patients were encouraged to empty their bowels prior to the CT simulation scan and before each treatment fraction. The CT datasets were transferred to the treatment planning system (TPS) for contouring and planning.

Target definition and dose prescription

Five intermediate to high-risk Prostate cancer patients previously treated with VMAT were selected for proton planning. For each patient, two proton plans were generated; planning target volume (PTV) 1 and PTV 2 respectively. This is a sequential treatment with the following target volume definitions and prescriptions:

PTV 1 was generated with a 0.5–0.7 cm expansion from PLNs CTV, 1 cm margin around prostate and seminal vesicles (Pro + SVs) except posteriorly, a 0.6 cm margin was given. 45 Gy in 25 fractions with 1.8 Gy per fraction was prescribed; PTV 2 was generated with a 1 cm expansion from CTV 2 (prostate and proximal seminal vesicles; Pro + proxSVs) and a 0.6 cm posterior margin. 34.2 Gy in 19 fractions with 1.8 Gy per fraction was prescribed. All OARs such as the rectum, bladder, bowel cavity and femurs were contoured as per RTOG contouring guidelines. Table 1 indicates the dose volume constraints for target coverage and OARs.

Treatment planning

Treatment planning for both modalities was performed using Eclipse treatment planning system (TPS) version 13.6 (Varian Medical Systems, Palo Alto, CA, US). All calculated plans were normalized such that at least 95% of the PTV volume received the prescription dose.

VMAT planning

VMAT plan for PTV 1 consists of two full arcs (179–181°; clockwise, 181–179°; counter clockwise) with a collimator tilt of 30°/330°. For PTV 2, an arc angle of 200–160° clockwise and 200–160° counter clockwise with a collimator tilt of 15°/345° was used. Plans were generated with a 10 MV energy and at a maximum dose rate (DR) of 600 MU/min. VMAT plans were optimized using the Photon Optimizer (PO) to achieve the desired dose volume constraints by continuously varying the DR, multileaf collimator (MLC) positions and gantry rotational speed to optimize the dose distribution. Details about VMAT optimization process has been published elsewhere [12]. Planning optimization objectives were adjusted to prioritize target coverage while minimizing the dose to the OARs, especially at the high dose region of the rectum. Final dose calculations were done using anisotropic analytical algorithm (AAA) with a dose calculation grid size of 2.5 mm.

Table 1
Dose-volume constraints for target volumes and OARs.

Structures	Objectives
PTV1 and PTV2	$D_{95\%} \geq$ PD $D_{2\%} <$ 107%
CTV1 and CTV2	$D_{98\%} \geq$ PD $D_{2\%} <$ 107%
Rectum	$V_{50Gy} <$ 60% $V_{35Gy} <$ 65% $V_{25Gy} <$ 70% $V_{15Gy} <$ 75%
Bladder	$V_{50Gy} <$ 65% $V_{35Gy} <$ 70% $V_{25Gy} <$ 75% $V_{15Gy} <$ 80%
Bowel cavity	$V_{30Gy} <$ 40%
Femurs	$V_{5Gy} <$ 50%

PTV, planning target volume; CTV, clinical target volume; OARs, organs at risk; PD, prescription dose; Dx, dose received by target at a defined volume (x) in percentage; Vx, volume of OAR receiving a defined dose (x) in Gray.