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Split-VMAT technique to control the expiratory breath-hold time in liver stereotactic body radiation therapy

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ABSTRACT

Purpose: In this study, we demonstrate the feasibility of using split-arcs in volumetric modulated arc therapy (VMAT), tailored for expiratory breath-hold in stereotactic body radiation therapy (SBRT) for liver tumors. We compare it with three-dimensional conformal radiation therapy (3D-CRT) and continuous-VMAT, for ten randomly selected hepatocellular carcinoma cases.

Methods: Four coplanar and four non-coplanar beams were used for the 3D-CRT plans. A pair of partial arcs, chosen using a back-and-forth rotating motion, were used for the continuous-VMAT plans. Split-VMAT plans were created using the same arc range as the continuous-VMAT plans, but were split into smaller arcs (<90°), to simulate an expiratory breath hold of <15 s. The dose distribution, treatment delivery efficiency, and patient specific quality assurance of the split-VMAT, were verified to ensure that the outcomes were equal, or better than, those for 3D-CRT and continuous-VMAT. The prescription was 48 Gy/4 fractions, to 95% of the PTV, using 10 MV FFF X-ray beams.

Results: The mean dose of the liver-GTV was lower in the split-VMAT compared with that of 3D-CRT. Split-VMAT was more conformal compared with 3D-CRT. The total treatment time for split-VMAT was shorter than that of 3D-CRT. Similar dosimetric indices were observed for split-VMAT and continuous-VMAT. All VMAT plans passed the gamma acceptance test.

Conclusions: Split-VMAT designed to accommodate an expiratory breath-hold period of 15 s is a feasible and efficient use of liver SBRT, because it does not compromise the quality of the plan, when compared with 3D-CRT or continuous-VMAT.

1. Introduction

In the past decade, radiotherapy was neither the primary, nor the major, treatment used for hepatocellular carcinoma (HCC) since conventional radiotherapy may lead to radiation-induced liver disease [1]. Recent studies have reported the efficacy of using stereotactic body radiation therapy (SBRT) for liver tumors [2,3]. SBRT is a hypo-fractionation regimen that is used to treat both resectable and unresectable tumors, with a biologically effective dose of about 100 Gy, assuming a α/β ratio of 10 Gy (BED_{10}) [4,5]. Since liver is a moving organ, it is necessary to reposition the liver tumor throughout the treatment course, to ensure that the dose is high at the tumor, but falls off rapidly in the adjacent healthy tissues [6].

Respiratory motion is one of the factors that contribute to tumor motion. The management of respiratory motion, along with a comprehensive review of different methods can be found in the Report of AAPM Task Group 76 [7]. Among the techniques that are discussed, breath-hold is a non-invasive and cost effective approach for minimizing respiratory motion. Breath-hold performed at the expiratory phase can better reproduce the tumor position compared with the inspiratory phase [8,9]. Moreover, the stability of expiratory breath-holding has been shown to be a reliable and clinically applicable for liver tumors [10]. Breath-holding techniques have the potential to improve the sparing of healthy tissue; however, the breath-holding tolerability may vary from one patient to another. Training is essential for a patient to

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establish a good breathing routine prior to the treatment; and the ideal breath-hold duration was recommended to be less than 30 s [11].

Besides respiratory motion, treatment with longer irradiation time is also a concern as it further contributes to intra-fraction treatment motion [12]. An advanced form of intensity modulated radiation therapy (IMRT), known as volumetric modulated arc therapy (VMAT), delivers radiation in a continuous gantry motion with differing gantry speed, multileaf collimator (MLC) speed, and dose rate [13,14]. It has been shown to potentially reduce the treatment time, without compromising the quality of the plan, when compared with IMRT for different cancers [15,16]. Moreover, the delivery efficiency and dosimetric accuracy in sparing the contralateral healthy tissues has been shown to be improved when using a partial arc rather than full arc geometry [17].

Since the delivery time of VMAT is dependent on the angular velocity (i.e., degrees of gantry rotation per second) of the linear accelerator, we speculate that liver SBRT may benefit from the use of VMAT, where the range of the arc is split to accommodate expiratory breath-hold because the respiratory motion management is an important procedure in SBRT. In this paper, we show that split-VMAT used with expiratory breath-hold is a feasible clinical implementation for liver SBRT. Which is especially true if, the quality of the treatment plan and patient safety were equal or better than those of three-dimensional conformal radiation therapy (3D-CRT) and continuous-VMAT considering the following parameters: (i) the dose distribution, (ii) the treatment delivery efficiency, and (iii) the patient specific quality assurance (QA).

2. Materials and methods

2.1. Treatment simulation and planning

In this study, the use of clinical materials has been approved by the Institutional Review Board of Hiroshima University. Ten HCC patients were selected at our institution with an age range of 56–81. Reproducibility of tumor position was confirmed within 5 mm using an X-ray fluoroscopy simulator (Acuity, Varian Medical Systems, Palo Alto, CA). Otherwise, Abches (Apex Medical Inc., Tokyo, Japan) was used as a monitor to self-control the respiratory motion and the tumor displacement. A comfortable expiratory breath-hold duration [8], of less than 15 s (10–14 s), was determined based on the patient's age. Radiation treatment planning images were taken, using a CT Lightspeed RT16 (GE Medical Systems, Hatfield, UK) scanner in which the first non-contrast scan was followed by contrast arterial, portal, and venous phases, under the expiratory breath-hold condition.

Radiation treatment plans were created using the Pinnacle^3 Planning System Version 9.6 (Philip, Fitchburg, WI), which was commissioned with the 5 mm MLC *TrueBeam* (Varian Medical Systems, Palo Alto, CA) linear accelerator. Delineation of the gross tumor volume (GTV) was based on the contrast arterial phase CT images, with the inclusion of iodized oil from the previous transarterial chemoembolization procedure. A clinical target volume (CTV) was defined as a 3–5 mm margin expansion around the GTV to include the presumed tumor cells. The planning target volume (PTV) was created with an expansion of 5–8 mm from the CTV, by taking the reproducibility of the tumor caused by respiratory motion and the setup uncertainties, into consideration. The patient demographics are summarized in Table 1.

Four coplanar and four non-coplanar beams were used for all 3D-CRT plans (Fig. 1a). The beam angle selection was case dependent, and the position of the MLC was manually adjusted in order to fit the prescribed isodose line to the PTV. Two sets of VMAT plans were prepared for each patient. For the first set of VMAT plans, a pair of partial arc ranges were chosen in a back-and-forth rotating manner, ipsilateral to the tumor, which will be referred to as continuous-VMAT plans (Fig. 1b). The second set of VMAT plans (split-VMAT) were created using the same arc range as the continuous-VMAT plans, but split into smaller arcs, to simulate an expiratory breath-hold of less than 15 s (Fig. 1c). An angular velocity of 6° gantry rotation per second was expected based on the specification of *TrueBeam*. Each split-arc was customized within 90° to simulate an expiratory breath-hold of less than 15 s. A total of six split-arcs were used, with an estimated gantry rotation time of 90 s per treatment fraction. The final gantry spacing was fixed at 4°, and a total of 45 control points were expected within one partial arc. SmartArc was used for the VMAT optimization. The optimization objectives and dose constraints are listed in Table 2. A PTV + 5 mm ring was created to conform the dose to PTV; and a PTV + 20 mm ring was used to reduce the dose to healthy tissues.

2.2. Beam energy, dose prescription, and dose calculation

In this study, beam energy of 10 MV, flattening filter free (FFF) was selected because HCC has a small target size, a sharp dose was needed to be produced in the center of the beam profile to reduce the dose outside the field [18]. A dose prescription of 48 Gy, in four fractions, was given to 95% of the volume of PTV. The maximum dose to GTV and PTV did not exceed 61 Gy. An adaptive convolution algorithm was used for the final dose calculation, with a grid size of $2 \times 2 \times 2$ mm^3, without virtual couch correction.

2.3. Treatment planning verification

Patient specific QA was performed to ensure that the continuous-VMAT and split-VMAT could deliver the doses as

Table 1
Patient demographics.

Patient	Age/Gender	Staging	Tumor		Region of interests (cc)		
			Location	Diameter (mm)	GTV	PTV	Liver-GTV
A	62/M	$T_1N_0M_0$	S6	19	1.6	10.5	948.2
B	77/M	$T_1N_0M_0$	S4	20	2.4	10.6	995.8
C	79/F	$T_2N_0M_0$	S5	37	1.6	11.3	1009.9
D	81/M	$T_1N_0M_0$	S6	30	0.8	17.0	921.4
E	69/F	$T_1N_0M_0$	S7	20	1.1	18.8	1986.9
F	63/M	$T_1N_0M_0$	S8	25	2.4	24.0	1726.5
G	56/M	$T_1N_0M_0$	S8	17	5.9	24.7	728.6
H	58/M	$T_2N_0M_0$	S4	20	3.0	29.1	1076.4
I	71/F	$T_1N_0M_0$	S8	10	18.4	57.1	1122.7
J	79/F	$T_1N_0M_0$	S4	32	27.6	87.3	1268.9
Mean	69.5	–	–	23.0	6.5	29.0	1178.5

Abbreviations: T, tumor; N, lymph nodes; M, metastasis; S, segment of liver; GTV, gross tumor volume; PTV, planning target volume; liver-GTV, liver minus gross tumor volume.

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