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Original article

Volumetric modulated arc therapy of head-and-neck cancer on a fast-rotating O-ring linac: Plan quality and delivery time comparison with a C-arm linac

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ABSTRACT

Background and purpose: Linac improvements in gantry speed, leaf speed and dose rate may increase the time-efficiency of volumetric modulated arc therapy (VMAT) delivery. The plan quality achievable with faster VMAT however remains to be investigated. In this study, a fast-rotating O-ring linac with fast-moving leaves is compared with a C-arm linac in terms of plan quality and delivery time for VMAT of head-and-neck cancer (HNC).

Material and methods: For 30 patients with HNC, treatment planning was performed using dual-arc (HA2) and triple-arc (HA3) VMAT on a Halcyon fast-rotating O-ring linac and using dual-arc VMAT on a TrueBeam C-arm linac (TB2). Target coverage metrics and complication probabilities were compared. Plan delivery was verified using 3%/3 mm gamma-index analysis of helical diode array measurements. Volumetric image acquisition and plan delivery times were compared.

Results: All studied VMAT-techniques fulfilled the target coverage objectives. $D_{2\%}$ to the boost volume was higher for HA2 (median 103.7%, 1st–3rd quartile [103.5%;104.0%]) and HA3 (103.2% [103.0%;103.7%)] than for TB2 (102.6% [102.3%;103.0%)], resulting in an increased boost target dose heterogeneity for HA2 and HA3. Complication probabilities were comparable between HA2 and TB2, while HA3 showed a xerostomia probability reduction (0.8% [0.2%;1.8%]) and dysphagia probability reduction (1.0% [0.2%;1.8%]) compared with TB2. Gamma-index agreement scores were never below 93.0% for HA2, HA3 and TB2. Volumetric imaging and plan delivery time was shorter for HA2 (1 m 24 s ± 1 s) and HA3 (1 m 54 s ± 1 s) than for TB2 (2 m 47 s ± 1 s).

Conclusion: For VMAT of HNC, the fast-rotating O-ring linac at least maintains the plan quality of two arcs on a C-arm linac while reducing the image acquisition and plan delivery time.

Radiation therapy of head-and-neck cancer (HNC) is often challenging due to the large, complex-shaped target volumes in close proximity to a large number of organs at risk (OAR). The introduction of intensity-modulated radiotherapy (IMRT) has led to reduced salivary dysfunction probability because of improved parotid gland sparing [1]. Moreover, IMRT has the potential to reduce swallowing dysfunction probability thanks to the improved sparing of swallowing structures [2]. The improved dose conformity of IMRT however generally comes at the expense of plan delivery time [3].

Increased time efficiency compared with 7–9 fields IMRT can be achieved with volumetric modulated arc therapy (VMAT) [4–8]. Single-arc plans have been shown to yield clinically acceptable plans for VMAT of HNC [8,9], while improvement in target coverage homogeneity and OAR sparing can be achieved by increasing the number of arcs [5,7,10,11]. This however requires additional beam-on time, indicating a trade-off between plan quality and delivery time [11].

A reduction in delivery time may positively impact clinical throughput and patient comfort. Such faster delivery could be achieved by utilizing increased dose rates, for instance using flattening filter free (FFF) beams [12]. The use of FFF for HNC VMAT, however, has not yet shown improvement in delivery efficiency, attributed to the current limitations in gantry and multi-leaf collimator (MLC) speed [12–14]. Improvements in speed of these linear

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accelerator (linac) components may therefore help in exploiting the potential advantage in delivery efficiency of FFF beams.

O-ring gantry designs are allowed to rotate at higher speeds than the one rotation per minute of current C-arm linacs, due to the encapsulation of the moving parts. The plan quality achieved with a faster VMAT delivery however remains to be quantified, since VMAT fluence distributions result from the interplay between gantry rotation, MLC leaf motion and dose rate [15]. Provided that a faster gantry rotation is supported by improved dose rate and leaf speed, the question remains open as well to which extent an effective improvement in delivery efficiency compared with a C-arm linac can be achieved.

A commercially available O-ring linac, Halcyon (Varian Medical Systems, Palo Alto, CA), combines a FFF beam with a higher gantry and MLC speed than current C-arm linacs, which may allow for improved time-efficiency of VMAT delivery. In the current study, this fast-rotating O-ring linac with fast-moving leaves is compared with a C-arm linac in terms of plan quality and delivery time for VMAT of HNC.

Materials and methods

Linac systems

The Halcyon IMRT/VMAT delivery system consists of a 6 MV FFF straight-through linac mounted on an O-ring gantry, which allows for a maximum rotation speed of 4 rpm. The jawless MLC is composed of two staggered layers of 28 leaf pairs, with a projected leaf width of 10 mm. The maximum leaf speed is 5 cm/s and the leaf span is 28 cm. For the delivery of VMAT for HNC, this fast-rotating O-ring linac was compared with a selected C-arm linac (TrueBeam, Varian Medical Systems), which has a maximum rotation speed of 1 rpm. On this C-arm linac, the used Millennium 120 MLC consists of 40 central leaf pairs of 5 mm width and 20 peripheral leaf pairs of 10 mm width, with a maximum leaf speed of 2.5 cm/s. The leaves are mounted on opposing, movable carriages and are subject to a maximum leaf span of 15 cm. On both systems the maximum dose rate was used, namely 6.0 Gy/min (at isocentre, for a 10×10 cm^2 field at 10 cm depth in water) on the fast-rotating O-ring linac and 4.8 Gy/min on the C-arm linac.

Patients and dose prescription

Computed tomography (CT) data of 30 patients with HNC, evenly distributed over three subsites (larynx, oropharynx and nasopharynx), were used (Table 1). The primary clinical target volume was delineated according to the clinical protocol in use. Neck lymph nodes and OAR were delineated according to published guidelines [16,17]. Planning target volumes (PTV) were created by isotropically expanding the clinical target volumes with 5 mm. For laryngeal and oropharyngeal cases, 70 Gy was prescribed to the high-risk PTV (PTV_{Boost}; primary tumour and positive neck) and 54.25 Gy to the low-risk PTV ($PTV_{Elective}$; elective neck), to be delivered in 35 fractions with a simultaneously integrated boost (SIB). For nasopharyngeal cases, prescription doses were 66.96 Gy and 59.4 Gy, to be delivered in 33 fractions with a SIB.

Planning objectives

PTV objectives were such that 98% of the PTV_{Boost} and $PTV_{Elective}$ volume received more than 95% of their respective dose prescription. Additional objectives were a near-maximum dose $D_{2\%}$ below 107% [18] of the high-dose prescription for PTV_{Boost} and PTV_{Total} (defined as the union of PTV_{Boost} and $PTV_{Elective}$). The objective for $PTV_{Elective\ only}$ (defined as $PTV_{Elective}$ minus PTV_{Boost} isotropically expanded with 5 mm) was a $D_{2\%}$ below 107% of the low-dose prescription. Planning risk volumes (PRV) were defined for the spinal cord (5 mm margin) and brainstem (3 mm margin). Hard constraints were used for their $D_{2\%}$ to remain strictly below 45 Gy and 50 Gy, respectively. For the OAR, priority was given to minimize the mean dose (D_{Mean}) to the contralateral (and if possible also to the ipsilateral) parotid gland to reduce risk of salivary dysfunction [19]. The next priority was to minimize D_{Mean} to the pharyngeal constrictor muscles (PCM) and supraglottic larynx, to reduce risk of swallowing dysfunction [20,21]. Finally, D_{Mean} to the oral cavity, glottic area and submandibular glands was minimized.

Planning techniques

Dual-arc VMAT on a C-arm linac (TB2)

A commonly used planning technique for VMAT of HNC on a C-arm linac [6,11,13,22,23], namely two arcs using a 6 MV flattened photon beam (TB2), was selected as a reference for comparison. For these TB2 plans on the C-arm linac, collimator angles were set at 10°/80°, with orthogonal leaf orientations for maximal OAR sparing but with a slight inclination with respect to the orientation plane and axis, respectively, to avoid cumulative tongue and groove effects [24]. For the frequent cases in HNC where the craniocaudal dimension of PTV_{Total} exceeded 15 cm, this setup would violate the 15 cm leaf span limitation for the second arc. Therefore the collimator angles were set at 10°/350° in those cases, using an 8 cm overlap symmetric around the isocentre.

Dual-arc (HA2) and triple-arc (HA3) VMAT on a fast-rotating O-ring linac

The VMAT planning technique studied on the fast-rotating O-ring linac consisted of two arcs (HA2), with collimators set at 10°/80° given the absence of any leaf span limitation. As the MLC system of the fast-rotating O-ring linac consists of broader leaves, an additional arc could be needed to achieve plan quality comparable to the TB2 reference on a C-arm linac. Therefore triple-arc VMAT (HA3) with collimators 10°/45°/80° was studied as well,

Table 1
Patient characteristics.

		Larynx	Oropharynx	Nasopharynx
Volume of target [cm^3]	**PTV_{Boost}**	134 (110–192)	237 (181–427)	253 (172–310)
	PTV_{Total}	462 (406–477)	573 (505–772)	861 (681–933)
Number of patients per UICC-stage	**I**	0 (0)	0 (0)	1 (0)
	II	1 (0)	0 (0)	2 (2)
	III	5 (1)	3 (3)	5 (5)
	IVa	4 (4)	6 (5)	2 (2)
	IVb	0 (0)	1 (1)	0 (0)

Abbreviations: UICC = International Union Against Cancer; PTV = Planning Target Volume.
The median PTV-volumes per subsite are shown, together with the 1st and 3rd quartile (between brackets). The number of patients per stage was determined according to the 7th UICC staging-edition. The number of patients with positive lymph nodes is shown between brackets.

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