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ORIGINAL ARTICLE

Volumetric Modulated Arc Therapy vs 3-Dimensional Conformal Radiotherapy in Head and Neck Cancer: a Comparative Planning and Dosimetry Study

SM Lee, CK Lee, KS Yu, KC Ngan

Department of Clinical Oncology, Queen Elizabeth Hospital, Hong Kong

ABSTRACT

Objective: *In this study, we evaluate the advantages of volumetric modulated arc therapy (VMAT) compared to conventional 3-dimensional conformal radiotherapy (3DCRT) with respect to dosimetry, verification, and treatment efficiency.*

Methods: *Seven patients with locally advanced squamous cell cancer of the head and neck treated by the VMAT and re-planned by 3DCRT techniques were studied retrospectively. The VMAT and 3DCRT plans were evaluated for (i) the homogeneity and conformity of radiation dose to the treatment targets, and (ii) doses to organs at-risk including the spinal cord and parotid glands. The treatment and verification time spent were estimated, so as to compare the efficiency of the VMAT and 3DCRT treatments.*

Results: *The median of the conformity and inhomogeneity indices of planning target volume 60 (to be covered by 60 Gy) were 1.60 and 6.1, respectively for VMAT, and 2.32 and 14.9, respectively for 3DCRT. The median maximum spinal cord dose of the VMAT plans was 38.9 Gy, compared to 44.5 Gy for the 3DCRT plans. Both parotids of two patients with central tumours could be spared for which the median dose was below 30 Gy. The contralateral parotid of all other patients with unilateral primary tumour could be spared except a patient with a close proximity tumour location. Compared to 3DCRT, the VMAT technique saved 4.25 machine-hours per patient for the full course of radiation treatment.*

Conclusions: *Compared to 3DCRT plans, VMAT plans produced significantly better target coverage as well as dose conformity. Doses to organs at-risk such as the spinal cord and parotid glands were also reduced. Besides, the delivery of VMAT treatment was more efficient.*

Key Words: *Head and neck neoplasms; Radiotherapy planning, computer-assisted; Radiotherapy, conformal; Treatment outcome*

中文摘要

頭頸癌的弧形調控放射治療與三維適形放射治療：治療計劃及放射劑量的比較研究

李淑敏、李志強、余啟成、顏繼昌

目的：評估弧形調控放射治療（VMAT）與三維適形放射治療（3DCRT）在放射劑量、驗證時間和治療效率三方面的比較。

Correspondence: *Ms SM Lee, Department of Clinical Oncology, Block R, Queen Elizabeth Hospital, 30 Gascoigne Road, Kowloon, Hong Kong.*
Tel : (852) 2958 6286 ; Fax : (852) 2958 5526; Email : lsm714@ha.org.hk, lck671@ha.org.hk

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方法：回顧研究七名原位末期鱗狀細胞頭頸癌患者，他們先接受VMAT，再以3DCRT跟進。然後評估兩種方法在以下兩方面的表現：（1）放射劑量到達目標器官的同質性和一致性；（2）到達高風險器官如脊髓和腮腺的放射劑量。估計治療及驗證時間，然後比較VMAT和3DCRT的治療效率。

結果：計劃靶區60（即用60 Gy）的一致性指標及非均勻指標的中位數方面，VMAT分別為1.60和6.1，而3DCRT分別為2.32和14.9。脊髓最大放射劑量的中位數，VMAT為38.9 Gy，3DCRT為44.5 Gy。兩名有中央腫瘤的患者，其腮腺的受照劑量中位數在30 Gy以下。至於其他有單側原發灶的病人，除了一名有近距離腫瘤的病人外，對側腮腺的受照劑量下降。與3DCRT比較，VMAT技術在放射治療整個過程中減低了每位病人4.25機器小時。

結論：與3DCRT比較，VMAT產生明顯更好的覆蓋目標及劑量一致性。到達高風險器官如脊髓和腮腺的放射劑量亦減少了。此外，VMAT有較高的治療效率。

INTRODUCTION

Regarding radiation treatment of squamous cell head and neck cancer (SCHNC) in our department, there has been a growing interest in replacing time-consuming conventional 3-dimensional conformal radiotherapy (3DCRT) techniques with volumetric modulated arc therapy (VMAT). The first linear accelerator capable of VMAT treatment was installed in our department in 2010, and VMAT treatment has been more commonly used since then. The advantages of VMAT include much reduced treatment time, improved patient comfort, improved machine throughput, and the potential for improved conformity and homogeneity of doses to targets.[1] The aim of this study was to evaluate the benefits of VMAT over 3DCRT for the radiation treatment of locally advanced SCHNC and to provide dosimetric and other logistic data in a cohort of patients. Ultimately, it aimed to facilitate technology transition and resources redistribution within the department.

Planning of the present study was performed to evaluate the differences in dose distribution using VMAT RapidArc (RA) radiotherapy technology (Varian Medical Systems, Palo Alto, CA, USA) and 3DCRT techniques in patients with SCHNCs, excluding nasopharyngeal carcinoma. The efficiency of both techniques for patient treatment was also compared.

METHODS

This was a retrospective study of seven patients with locally advanced SCHNC treated by VMAT from June 2010 to June 2011 (carcinoma of tonsil = 2, carcinoma of tongue = 1, carcinoma of oral cavity = 3, and carcinoma of hypopharynx = 1). The clinical parameters of these seven patients are described in Table 1. All planning target volumes (PTVs) for different dose levels were highly irregular and mostly concave-shaped wrapping around critical organs at-risk (OAR), which include the spinal cord and the parotid glands. These seven patients were re-planned for radiation treatment by the 3DCRT technique. The parallel opposing fields were used and if necessary matched with a lower cervical field using 6 MV photons. The low-energy posterior lateral electron fields were used to cover the part of the PTVs abutting and/or posterior to the spinal cord during the later phases of treatment when the size of the lateral opposing parallel photon fields were reduced to avoid the spinal cord after the spinal cord tolerance was reached in phase I. For both techniques, the photon dose calculation was performed using the anisotropic analytical algorithm which was the algorithm used in the Eclipse, version 8.6 treatment planning system (Varian Medical Systems, Palo Alto, CA).[2] The VMAT plans of the five patients with bilateral neck node metastases were generated using double full arcs. The remaining two VMAT plans treated the ipsilateral neck nodes only and were composed of one 360-degree full arc and another half arc (one clockwise and another counter clockwise arc rotation). The collimator rotation of the VMAT plans without an additional anterior cervical field was fixed to a value different from zero, to minimise the contribution of the tongue and groove effect.[3,4]

All 3DCRT plans were reviewed and approved as if they were used for radiation treatment by the same oncologist who approved the VMAT plans used for patients' actual treatment. The plans were compared to evaluate (i) the homogeneity and conformity of doses to targets, and (ii) doses to OAR, including the spinal cord and parotid glands.

Planning Target Volumes and Prescriptions

The dose prescription and fractionation of the radiation

Table 1. Clinical data and radiation treatment details of the seven patients.

Adverse event	Patient						
	A	B	C	D	E	F	G
Site of primary tumour	Tonsil	Tongue	Hypopharynx	Oral cavity	Floor of mouth	Tonsil	Alveolus
Staging	pT2N0	pT2N2	T2N2b	T4N2b	pT1N2b	T2N2b	T4N0
Postoperative treatment (chemoRT / RT alone)	Yes (RT alone)	Yes (RT alone)	No (ChemoRT)	No (ChemoRT)	Yes (ChemoRT)	No (RT alone)	No (RT alone)
PTV dose level (Gy)	54, 60, 66	54, 60, 64	60, 66	50, 70	50, 60, 64	60, 66	50, 70
No. of phases of VMAT (total fractions)	1 (30 frs)	1 (30 frs)	1 (30 frs)	2 (35 frs)	3 (32 frs)	1 (33 frs)	2 (35 frs)
No. of phases of 3DCRT (total/electron)	4/2e	4/2e	3/2e	3/1e	4/2e	3/1e	3/1e
Dose levels for different phases of 3DCRT	40,54,60,66	40,54,60,64	40,60,66	40,50,70	40,50,60,64	40,60,66	40,50,70

Abbreviations: ChemoRT = concurrent chemo-radiation; RT = radiotherapy; PTV = planning target volume; VMAT = volumetric modulated arc therapy; 3DCRT = 3-dimensional conformal radiotherapy.

treatment delivered by the VMAT plans are also listed in Table 1. Three patients were treated by VMAT with 60 Gy prescribed in 30 fractions in six weeks, with simultaneous integrated boosts up to 64 to 66 Gy intended for a smaller PTV during each six-week treatment. Two of the three patients had a lower-dose PTV (treated to 54 Gy in six weeks). Another patient received 66 Gy in 33 fractions over 6.5 weeks with a lower-dose PTV treated to 60 Gy. The other three patients received full dose through VMAT in two to three phases. The prescription dose was 50 Gy in 25 fractions in five weeks during the first phase and a final total cumulative dose up to 64 to 70 Gy delivered in an additional second phase with or without a third phase. All the seven 3DCRT plans were prepared to treat the higher-dose PTVs at 64, 66, or 70 Gy for different patients with different phases.

The lower-dose PTVs were prescribed in VMAT in the five patients; PTVs at 50 and 54 Gy were grouped together as 'PTVlow' for combined analysis, while PTVs at 64, 66 and 70 Gy of different patients were grouped as 'PTVhigh' for joint analysis. Therefore, the three groups of PTVs to be analysed were PTVlow (n=5), PTV60 (n=5), and PTVhigh (n=7). The threshold for statistical significance was $p \leq 0.05$. All statistical tests were two-sided, and all analyses were carried out using the Statistical Package of Social Sciences (SPSS version 16).

Evaluation Criteria

For all patients, cumulative dose-volume histograms and dosimetry parameters were calculated and compared for different PTVs and OARs. Mean and maximum VMAT and 3DCRT doses within the PTVs were also analysed and compared in individual patients. Target dose conformity was determined by comparing the volume of the PTV with volumes covered by the 95% isodose surface. The conformity index was calculated according to the following formula: 95%-isodose-volume/volume of PTV.[5,6] In addition, the dose inhomogeneity index within the PTV was defined as (D5%-D95%)/Dmean.[7]

The tolerance of the individual OARs was defined as below: 54 Gy maximum for brainstem, 45 Gy

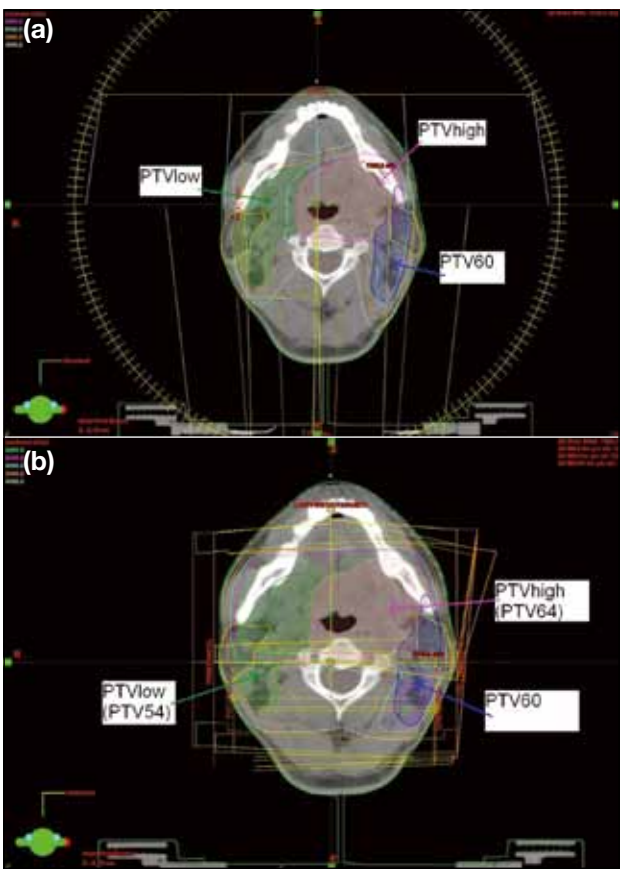

Figure 1. Patient B: (a) dose distribution of the volumetric modulated arc therapy plan and (b) dose distribution of the 3-dimensional conformal radiotherapy plan.

maximum for spinal cord, and a median dose of 30 Gy for the parotid glands (at least one parotid). As the brainstem dose was not a limiting factor for all seven cases, detailed analysis of the dose to the brainstem was excluded from this study.

RESULTS

The isodose distributions in the VMAT and 3DCRT plans and the dose-volume histogram of one patient are shown in Figures 1 and 2, respectively. One of the patients with planning target volume of 70 is shown in Figure 3.

The Wilcoxon matched-pair signed-rank test was conducted to determine whether there were differences in the mean dose, conformity index, and inhomogeneity index of PTVlow, PTV60 and PTVhigh, as well as the maximum spinal cord dose used for the VMAT and 3DCRT plans.

Table 2. Median and range of dose parameters of 3-dimensional conformal radiotherapy (3DCRT) and volumetric modulated arc therapy (VMAT) plans for head and neck cases.

Variable	Median (min, max)		p Value
	VMAT	3D CRT	
Mean dose (Gy)			
PTVlow	58.5 (56.9, 64.0)	63.8 (56.2, 67.0)	0.14
PTV60	63.8 (63.0, 64.1)	62.6 (60.8, 65.9)	0.50
PTVhigh	68.7 (55.0, 74.3)	67.9 (64.4, 72.0)	0.02
Conformity index (95% CI)			
PTVlow	1.65 (1.45, 2.33)	2.71 (2.20, 3.18)	0.04
PTV60	1.60 (1.16, 2.01)	2.32 (1.41, 3.73)	0.04
PTVhigh	2.29 (1.43, 3.46)	3.00 (2.14, 8.29)	0.02
Inhomogeneity index			
PTVlow	10.9 (4.2, 21.1)	18.1 (13.7, 22.7)	0.04
PTV60	6.1 (4.3, 8.7)	14.9 (13.5, 16.2)	0.04
PTVhigh	5.3 (3.5, 6.2)	5.8 (3.7, 12.0)	0.31
Maximum spinal cord dose (Gy)	38.9 (33.4, 42.5)	44.5 (38.6, 45.3)	0.04

As indicated in Table 2, there was a statistically significant difference in the dose parameters of the two techniques for the various PTVs and the OARs. It was found that 3DCRT technique had a significantly worse conformity index (PTV60: VMAT vs 3DCRT = 1.60 vs 2.32) and inhomogeneity index (PTV60: VMAT vs 3DCRT = 6.1 vs 14.9) at all PTV levels. It can be concluded that all VMAT plans have much better conformity and homogeneity than all 3DCRT plans.

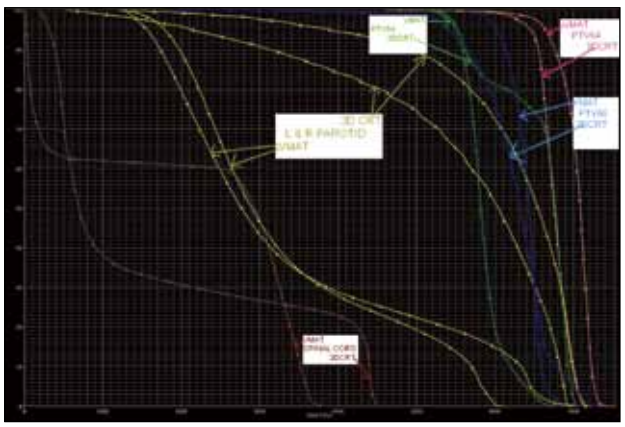

Figure 2. Dose-volume histogram of patient B.

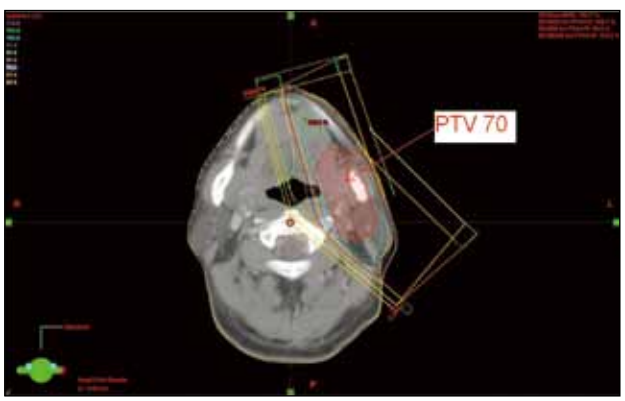

Figure 3. Planning target volume 70 of patient D.

For the OARs, the maximum spinal cord dose of VMAT plans were significantly lower than those from 3DCRT plans as shown in Table 2, confirming that VMAT plans can provide better protection to OARs.

As shown in Table 3, the global hotspots of VMAT and 3DCRT plans were comparable. The hotspot doses of 3DCRT plans with electron fields were significantly higher as shown in Table 3.

In general, a lower dose was delivered to OARs by VMAT plans as shown in Table 3. We took the tolerance dose for the parotid gland to be below a median of 30 Gy. Both parotid glands of two patients with central tumours could be spared and the median dose to the parotid was below 30 Gy (Table 3). The contralateral parotids in four out of five patients (except patient F) with unilateral primary tumour could be spared. For patient F, the tumour location was in close proximity to the parotid glands and the overlapped volume of the parotid glands and the PTV was large. As a result, the contralateral parotid of patient F was sacrificed. The median maximum spinal cord dose in

Table 3. Median contralateral parotid doses and hotspot doses of volumetric modulated arc therapy (VMAT) and 3-dimensional conformal radiotherapy (3DCRT). Data with grey shading were from the plans with electron fields.

	Patient A		Patient B		Patient C		Patient D		Patient E		Patient F		Patient G	
Hotspot (%)	VMAT	3DCRT	VMAT	3DCRT	VMAT	3DCRT	VMAT	3DCRT	VMAT	3DCRT	VMAT	3DCRT	VMAT	3DCRT
Global hotspot	114.2	110.4	115.1	109.2	111.7	114.7	111.6	108.4	110	109.3	108.8	117.5	110.7	108.6
Phase 1		111.3		110		109.3	114.2	109.6	113.9	112.5		107.5	113.5	109.4
Phase 2		122.3		148.1		144.2	112.3	141.5	115.4	130.4		142.9	111.1	147.6
Phase 3		120.4		132.4		131.7		109.7	112.4	124.9		109.5		109.5
Phase 4		110.2		109						116.6				
Primary tumour	Unilateral		Central		Central		Unilateral		Unilateral		Unilateral		Unilateral	
Median dose of contralateral parotid	29.0	60.4	N/A		N/A		21.3	69.2	23.0	52.39	>30		19.5	38.8
Median dose of both parotids	N/A		Lt 23.3 Rt 21.7	60.1 58.4	Lt 26.7 Rt 18.0	57.2 56.3	N/A		N/A		N/A		N/A	

Abbreviation: N/V = not available.

Table 4. Comparison of the technical aspects and estimated time for computer planning, simulator verification, and treatment implementation of 3-dimensional conformal radiotherapy (3DCRT) versus volumetric modulated arc therapy (VMAT).

Procedure	3DCRT	VMAT
Computer planning	Phase I: Lateral opposing parallel fields using 6 MV photons ± anterior cervical field (20 fractions) Phase II: Lateral opposing parallel fields using 6 MV photons; posterior cervical fields using electrons ± anterior cervical field (5 fractions) Phase III: same as phase II with different field sizes (5 fractions) Phase IV: Lateral opposing parallel fields (if applicable) Generation time: 1 to 1.5 working days	One phase only using 2 arcs ± anterior cervical field (about 30 fractions) Generation of backup IMRT plans is required Generation time: 1-2 working days for VMAT plans and 0.5 days for IMRT backup plan
Simulator verification	Verify iso-centres of 3DCRT plans Take simulator film of anterior cervical fields and electron fields	Verify iso-centres of VMAT plans Take simulator film of anterior cervical field if necessary
Treatment time per fraction	Phase I: 15-20 minutes Phase II: 30-45 minutes Phase III: 30-45 minutes Phase IV: 15 minutes (if applicable)	15 minutes
Total treatment and verification time per patient	Treatment time: 15.5 hours Verification time: 0.5 hours Total machine hours: 16 hours	Treatment time: 10 hours Verification time: 1.75 hours Total machine hours: 11.75 hours

Abbreviation: IMRT = intensity-modulated radiotherapy.

the VMAT plans was 38.9 Gy, compared to 44.5 Gy in the 3DCRT plans, both of which were lower than the tolerance dose of 45 Gy for the spinal cord.

DISCUSSION

Compared to 3DCRT plans, VMAT plans provide better dose homogeneity and highly conformal dose distributions. Doses to OARs such as the spinal cord and parotid glands were also reduced. This could allow dose escalation by VMAT to tumour in close proximity to the spinal cord and parotid glands, so that local tumour control could be enhanced. In contrast, the reduction of the OAR (spinal cord) irradiation in 3DCRT treatments to avoid the risks of late toxicity necessitates a compromise of the dose to the PTV.

Dose heterogeneity, partly brought about by the presence of hotspots in the 3DCRT plans due to matching of electron fields with photon fields, may increase the risk of complications, such as carotid artery stenosis.[8,9] The chance of post-treatment radiation-induced carotid artery stenosis can be reduced by using VMAT to treat SCHNC. Moreover, the Simultaneous Modulated Accelerated RadioTherapy (SMART) plan of VMAT can attain higher homogeneity. So SMART plans are generally recommended for VMAT whenever the difference in PTV dose levels is small.[7]

Apart from the above-mentioned superiority of the VMAT plans, treatment time (beam on and set-up time) and efficiency is another important issue. This

is especially relevant for locally advanced SCHNC patients with tracheostomy in whom a shorter treatment delivery time is usually preferred to maintain a stable patient position throughout the radiation procedure. Table 4 shows that the delivery efficiency by the VMAT plan was much higher than that of the 3DCRT plans requiring electron fields. Moreover, the verification time for the latter plans was much longer than that for VMAT plans (for which only one iso-centre for set-up was required). The estimated total treatment time and verification time for the 3DCRT technique were 15.5 and 0.5 hours per patient, respectively. Thus a total machine time of 16 hours was required for the full course of 3DCRT treatment. The estimated total treatment time and verification time for the VMAT technique were 10 and 1.75 hours per patient, respectively. The corresponding total machine time saved, if VMAT were used, would be 4.25 machine hours per patient (i.e. 16 minus 11.75 hours; Table 4).

Quality assurance procedures before treatment are necessary for VMAT plans but not for 3DCRT plans. The disadvantage of the VMAT planning technique at present is the longer time required for creating the plan compared to 3DCRT. As there was only one linear accelerator with VMAT capability in our department until recently, backup intensity-modulated radiotherapy (IMRT) plan had been necessary all along, which further increased computer planning time. With the installation of an additional VMAT facility in the near future, backup IMRT plans will become unnecessary and the overall time saved by VMAT treatment compared to 3DCRT treatment would be even greater.

CONCLUSION

Compared to 3DCRT plans, VMAT plans produce significantly better target coverage as well as dose conformity. Doses to OARs such as the spinal cord and parotid glands are also reduced. Besides, VMAT treatment is more efficient than 3DCRT treatment for SCHNC. In our department, priority cases will be treated by VMAT.

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