Evaluation of the trade-offs encountered in planning and treating locally advanced head and neck cancer: intensity-modulated radiation therapy vs dual-arc volumetric-modulated arc therapy

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Objective: The primary purpose of this study was to assess the practical trade-offs between intensity-modulated radiation therapy (IMRT) and dual-arc volumetric-modulated arc therapy (DA-VMAT) for locally advanced head and neck cancer (HNC).

Methods: For 15 locally advanced HNC data sets, nine-field step-and-shoot IMRT plans and two full-rotation DA-VMAT treatment plans were created in the Pinnacle³ v. 9.0 (Philips Medical Systems, Fitchburg, WI) treatment planning environment and then delivered on a Clinac iX (Varian Medical Systems, Palo Alto, CA) to a cylindrical detector array. The treatment planning goals were organised into four groups based on their importance: (1) spinal cord, brainstem, optical structures; (2) planning target volumes; (3) parotids, mandible, larynx and brachial plexus; and (4) normal tissues.

Results: Compared with IMRT, DA-VMAT plans were of equal plan quality ($p > 0.05$ for each group), able to be delivered in a shorter time (3.1 min vs 8.3 min, $p < 0.0001$), delivered fewer monitor units (on average 28% fewer, $p < 0.0001$) and produced similar delivery accuracy ($p > 0.05$ at $\gamma_{2\%/2\text{mm}}$ and $\gamma_{3\%/3\text{mm}}$). However, the VMAT plans took more planning time (28.9 min vs 7.7 min per cycle, $p < 0.0001$) and required more data for a three-dimensional dose (20 times more, $p < 0.0001$).

Conclusions: Nine-field step-and-shoot IMRT and DA-VMAT are both capable of meeting the majority of planning goals for locally advanced HNC. The main trade-offs between the techniques are shorter treatment time for DA-VMAT but longer planning time and the additional resources required for implementation of a new technology. Based on this study, our clinic has incorporated DA-VMAT for locally advanced HNC.

Advances in knowledge: DA-VMAT is a suitable alternative to IMRT for locally advanced HNC.

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The use of intensity-modulated radiation therapy (IMRT) to treat locally advanced head and neck cancer (HNC) is supported by a number of clinical trials which confirm its ability to limit xerostomia [1, 2], while other trials have noted that IMRT provides improved 2-year overall survival [3, 4], progression-free survival [3, 4] and locoregional control [4, 5].

Recently, volumetric-modulated arc therapy (VMAT) has emerged as an efficient delivery technique that is able to deliver high sculpted radiation dose distributions in one or two arcs [6]. The main advantage in implementing VMAT is a marked reduction in overall treatment time, which is advantageous because VMAT promises an increase in throughput for hospital administrators and less time on the treatment couch for patients. However, it is still unclear whether IMRT and

VMAT treatment plans are equivalent for a challenging disease site such as HNC. This point has been recently debated for single-arc VMAT [7].

To date, there have been a limited number of articles that have investigated VMAT for HNC [8–13]. Vanetti et al [8] compared single- and dual-arc VMAT (DA-VMAT) against sliding window IMRT (SW-IMRT), and found improved target coverage and organ-at-risk (OAR) sparing. Verbakel et al [9] planned and delivered VMAT plans for 12 HNC patients previously treated with IMRT and concluded that DA-VMAT provided similar sparing and better target homogeneity than single-arc VMAT or IMRT. Bertelsen et al [10] compared VMAT treatment planning of 25 previously treated HNC patients' IMRT plans and concluded that single-arc VMAT produced equivalent coverage and sparing of OARs to step-and-shoot IMRT. Doornaert et al [11] examined 35 HNC patients previously treated with DA-VMAT, but did not do a comparison with IMRT. Johnston et al [12] investigated dual-arc treatment planning as compared with IMRT, and determined that both IMRT and VMAT resulted in acceptable plans, with VMAT delivering approximately one-third of the monitor units (MUs) compared with SW-IMRT. Stieler et

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al [13] investigated HNC planning for the treatment of 10 patients planned with serial tomotherapy, seven- and nine-field step-and-shoot IMRT, and single-arc VMAT. The study determined that IMRT provided the best sparing of OAR, but VMAT provided the most efficient treatment in terms of MU and treatment time. Table 1 summarises the pertinent HNC treatment studies using VMAT.

Our study is different from the previous VMAT HNC studies [8–13] in that it specifies a prioritised set of treatment planning goals prior to treatment planning and then primarily evaluates the ability to meet these prioritised goals. A recent critique of treatment plan comparisons of IMRT and VMAT recommends the use of goal programming, where multiple goals are set out prior to optimisation [14], as is done in this study. In addition, they recommend that the inverse planning objectives are reflective of how the plans are evaluated. In this study we were cognisant of this criticism and created inverse planning objectives based on an ordered set of planning goals (as recommended), then evaluated plans based on these same ordered set of planning goals. The ability to meet the prioritised treatment planning goals will be the primary end point for evaluation.

The secondary points of evaluation of these plans represent the trade-offs. Although each of the prior studies have addressed some of these trade-offs, none has completely addressed the ones investigated in this study, as outlined in Table 1. The secondary end points can be viewed as the trade-offs that healthcare administrators/treating radiation oncologists should consider when deciding which technique to implement.

Methods and materials

Patient population and contouring

A total of 15 locally advanced HNC CT data sets were selected for this study with staging, planning target volumes (PTVs) and patient information as defined in Table 2. All of the contours were created with strict adherence to the rules set out in the National Cancer Institute of Canada (NCIC) HN.6 clinical trial [15]. The patient CT scans were contoured with three PTVs: PTV70, which includes primary tumour and involved nodes; PTV63, which includes high-risk nodes; and PTV56, which includes low-risk nodes. Additional contours that were created include brainstem, planning risk volume (PRV) for brainstem created using 5-mm expansion, spinal cord, PRV for spinal cord created using 5-mm expansion, optic structures, parotids, mandible, glottic larynx, brachial plexus, midline mucosal structures and non-specified tissues (within external but not part of any PTV or OAR). Modified PTVs (modPTVs) were created to constrain these structures 5 mm from the external contour. Optimisation PTVs (optPTVs) are evaluated to only contain one dose level, and therefore the contours for these structures are truncated at where they overlap with higher-dose modPTVs. The treatment prescription was at least 70 Gy to 95% of the modPTV70.

Table 1. An overview of studies found to October 2011 that investigated volumetric-modulated arc therapy for locally advanced head and neck cancer

Reference	Number of cases	Technique compared	Number of arcs	PTV Number	HD (Gy)	TPS	Linear accelerator	Ordered goals?	Trade-offs investigated			
									MU	PT	TT	DC
Vanetti et al [8]	29	SW	1,2	3	66	^a Eclipse™	Varian Medical Systems	N	Y	N	N	N
Verbakel et al [9]	12	SW	1,2	2	70	^a Eclipse	Varian Medical Systems	N	Y	N ^d	Y	Y
Bertelsen et al [10]	25	SS	1	3	66, 68	^b Pinnacle ³	Elekta AB	N	Y	N	Y	Y
Doornaert et al [11]	35		2	2	70	^a Eclipse	Varian Medical Systems	N	N	N ^d	N	N
Johnston et al [12]	10	SW	2	3	70	^a Eclipse	Varian Medical Systems	N	Y	N	N	N
Stieler et al [13]	10	SS, ST	1	2	60	^c Monaco®	Elekta AB	N	Y	N	Y	Y

DC, delivery comparison; HD, high-dose planning target volume prescription dose; MUs, monitor units; N, no; PT, planning time; PTV, planning target volume; SS, step-and-shoot intensity-modulated radiation therapy; ST, serial tomotherapy; SW, sliding window intensity-modulated radiation therapy; TPS, treatment planning system; TT, treatment time; Y, yes.

^aManufactured by Varian Medical Systems, Palo Alto, CA.

^bManufactured by Philips Medical Systems, Fitchburg, WI.

^cManufactured by Elekta AB, Stockholm, Sweden.

^dData recorded only for volumetric modulated arc therapy.

Table 2. A summary of the disease type, TNM (tumour–node–metastasis) staging and planning target volumes for the 15 cases analysed in this study

Number	Primary disease location	TNM staging	PTV70 volume (cm ³)	PTV63 volume (cm ³)	PTV56 volume (cm ³)
1	Larynx	T4a N0 M0	100.6	17.7	1097.3
2	Tonsil	T3 N2c M0	384	202	916.3
3	Base of tongue	T2 N3 M0	483.7	214.6	517.1
4	Base of tongue	T1 N2a M0	162.9	142.6	739
5	Tonsil	T1 N2b M0	150.7	181.2	763.1
6	Tonsil	T2 N2c M0	239.7	56.9	951.9
7	Larynx	T3 N1 M0	124.3	59.3	540.5
8	Base of tongue	T4a N2c M0	363.3	375.6	1129.05
9	Hypopharynx	T4b N2b M0	388.2	371.2	550.1
10	Tonsil	T3 N2b M0	225.4	212.2	838.4
11	Oropharynx	T4a N2c M0	351	106.6	1094.79
12	Base of tongue	T1 N2 M0	223.6	92.7	1100.1
13	Tonsil	T2 N2c M0	236.3	66.7	1250.9
14	Base of tongue	T3 N2c M0	277.3	70.7	789.1
15	Base of tongue	T3 N3 M0	345.6	253.8	918.8

PTV56, planning target volume including low-risk nodes; PTV63, planning target volume including high-risk nodes; PTV70, planning target volume including primary tumour and involved nodes.

Definition of treatment planning goals

The treatment planning priorities are clearly presented in the NCIC HN.6 clinical trial as:

- (1) critical OARs and PRV
- (2) PTV coverage

- (3) non-critical OAR
- (4) undefined normal tissues [15].

The NCIC HN.6 prioritised planning goals organised by importance group are included in Table 3, which was used to guide the treatment planners when optimising the HNC treatment plans.

Table 3. A summary of the treatment planning criteria for all plans included in the study grouped into four priority groups

Priority group	Organ	Dose	Volume
1	Brainstem	<54 Gy	–
	Brainstem	<50 Gy	0.1 cm ³
	PRV BS 5 mm	<60 Gy	0.1 cm ³
	Spinal cord	<48 Gy	–
	Spinal cord	<45 Gy	0.1 cm ³
	PRV SC 5 mm	<52 Gy	0.1 cm ³
	Optic chiasm	<45 Gy	–
	Globe	<45 Gy	–
	Optic nerve	<45 Gy	–
2	modPTV70	>65.1 Gy	99%
	modPTV70	>70 Gy	95%
	modPTV70	<77 Gy	20%
	modPTV70	Mean <73.5 Gy	
	modPTV70	<80.5 Gy	0.01% (maximum)
	modPTV63	>58.6 Gy	99%
	modPTV63	>63 Gy	95%
	modPTV63	<69.3 Gy	20%
	modPTV63	<75.6 Gy	0.01% (maximum)
	optPTV56	>52.8 Gy	99%
	optPTV56	>56 Gy	95%
	optPTV56	<61.6 Gy	20%
3	optPTV56	<70 Gy	0.01% (maximum)
	Left or right parotid	Mean <26 Gy	
	Left or right parotid	<20 Gy	20 cm ³
	Left or right parotid	Median <30 Gy	
	Mandible	<75 Gy	0.1 cm ³ (maximum)
	Glottic larynx	<50 Gy	0.1 cm ³ (maximum)
4	Brachial plexus	<63 Gy	–
	Normal midline (not PTV)	<60 Gy	–
	Mucosal surfaces (not PTV)	<60 Gy	–
	Unspecified tissue (i.e. not PTV, PRV, OAR)	<77 Gy	1%/1 cm ³

BS, brainstem; modPTV63, modified planning target volume including high-risk nodes; modPTV70, modified planning target volume including primary tumour and involved nodes; OAR, organ at risk; optPTV56, optimisation planning target volume including low-risk nodes; PRV, planning risk volume; PTV, planning target volume; SC, spinal cord.

Group 1, critical structures; Group 2, PTVs; Group 3, non-critical structures; Group 4, normal tissue.

Step-and-shoot intensity-modulated radiation therapy treatment planning

Treatment planning for step-and-shoot IMRT was done using the Pinnacle³ v. 9.0 software (Philips Medical Systems, Fitchburg, WI). Our Pinnacle³ planning environment has incorporated the SmartAccess Enterprise solution, which involves thin client workstations and computation using a remote compute module consisting of six Intel® Xeon® Quad Core processors (Intel Corporation, Santa Clara, CA) running at 3.0 MHz per core. Nine equally spaced beams were selected with jaw positions automatically chosen by the treatment planning system (TPS). Additional relevant TPS parameters that were used for all plans were: maximum number of segments: 72; minimum segment area: 8 cm²; minimum MUs per segment: 6; minimum number of leaf pairs: 2; and minimum leaf end separation: 2 cm. The treatment plan optimisation was run until there was no further improvement in the plans by a single planner (DM). All final dose calculations were done using collapsed cone convolution (CCC) using a dose grid of 0.3 × 0.3 × 0.3 cm. The IMRT dose files were exported to determine the memory required to store the three-dimensional (3D) dose distribution.

Volumetric-modulated arc therapy treatment planning

DA-VMAT plans were created within the SmartArc module Pinnacle³ v. 9.0. The first arc was a clockwise (CW) arc with arc ranges from -180.1° to 179.9°, and the second anticlockwise (ACW) arc had arc ranges of 179.9° to -180.1°. The sequence of CW followed by ACW allows for efficient DA-VMAT delivery. The jaw positions for the DA-VMAT fields were automatically chosen and relevant delivery parameters that were used for SmartArc optimisation were: collimator angle: 45°; final gantry spacing: 4°; maximum delivery time: 90 s; and constrain leaf motion: 0.46 cm deg⁻¹. Similar to IMRT, the plans were optimised until no further improvements in the plans were observed and all plans were calculated in CCC, with a dose grid of 0.3 × 0.3 × 0.3 cm. The final dose distribution was exported and the time to complete one optimisation cycle and final dose calculation was recorded for both IMRT and DA-VMAT.

Treatment planning analysis for the group

The treatment plans were analysed by the ability to meet the treatment planning goals as described in Table 3. The treatment planning goals were assessed by group with a binary metric where the goal was either achieved (1) or not achieved (0). The average pass rate for the group was analysed.

Treatment planning analysis per case

The ability to meet treatment planning goals was also assessed for each individual case. A treatment quality score (TQS) was created using the following formula:

$$TQS_{i,j} = 4 \cdot f_1 + 3 \cdot f_2 + 2 \cdot f_3 + 1 \cdot f_4 \quad (1)$$

The TQS is indexed for patient i and treatment type j (either IMRT or DA-VMAT), and f_k is the fraction of treatment goals met for the priority group k . The treatment quality score provides a metric that provides a weighting arrangement that is specified in the NCIC HN.6 clinical trial providing scores from 0 (no planning goals met) to 10 (all planning goals are met). The TQS is useful because it provides a way to compare treatment plans from different treatment techniques for the same case.

Additional dosimetric analysis

In addition, various other dosimetric parameters were analysed for IMRT and DA-VMAT treatment plans, including D_{mean} , $D_{99\%}$ (minimum dose received by 99% volume of structure) and $D_{1\%}$ (minimum dose received by 1% volume of structure), for all of the PTVs, the $D_{95\%}$ for the modPTV70, as well as the maximum dose ($D_{0.1\text{cc}}$) to the spinal cord and brainstem and the mean dose (D_{mean}) to the lowest dose parotid. The homogeneity index (HI) was determined to be $D_{1\%}$ divided by the $D_{99\%}$ for the PTVs.

Step-and-shoot intensity-modulated radiation therapy and dual-arc volumetric-modulated arc therapy delivery

Delivery of the step-and-shoot IMRT and DA-VMAT plans was performed on a VMAT-enabled Varian Clinac iX linear accelerator (Varian Medical Systems, Palo Alto, CA). All treatment plans were delivered to the ArcCHECKTM cylindrical array detector (Sun Nuclear Inc., Melbourne, Australia) and the files were recorded for further analysis. In addition, the Varian log files were also saved to determine the delivery time (recorded as time between first beam-on and last beam-off).

Delivery analysis

The IMRT and DA-VMAT ArcCHECK results were analysed in MapCHECK v. 5.2.0 software (Sun Nuclear Inc.) using the gamma analysis with %Diff=3%/distance to agreement (DTA)=3 mm and %Diff=2%/DTA=2 mm. The pass rates were recorded for IMRT and DA-VMAT deliveries for each technique and analysed.

Statistical analysis

Statistical analysis was performed using the Wilcoxon rank-sum test using MATLAB v. r2009B (MathWorks, Natick, MA).

Results

Treatment planning goal comparison for the entire group

The treatment planning goals were compared for the 15 IMRT and DA-VMAT treatment plans. The priority 1

treatment planning goals (*i.e.* critical OARs) had $100 \pm 0\%$ compliance for both IMRT and DA-VMAT. The priority 2 treatment planning goals (*i.e.* PTVs) were met in the IMRT plans with a compliance percentage $91.8 \pm 10.3\%$ as compared with the DA-VMAT compliance percentage of $92.8 \pm 10.3\%$ ($p > 0.05$). For the priority 3 treatment planning goals (*i.e.* non-critical OARs), the IMRT plans had a compliance percentage of $65.0 \pm 18.4\%$ and the DA-VMAT plans had a compliance percentage of $65.6 \pm 19.1\%$ ($p > 0.05$). Finally, for the priority 4 treatment planning goals (*i.e.* normal tissues) the compliance percentage for IMRT was $86.7 \pm 22.9\%$ and for VMAT was $83.3 \pm 24.4\%$ ($p > 0.05$).

Treatment quality score for each individual case

The TQS was equal for IMRT and DA-VMAT for 12 out of 15 of the cases, while the IMRT TQS was higher (*i.e.* superior) for 1 out of 15 cases and the DA-VMAT TQS was higher for 2 out of 15 cases. The mean TQS score for IMRT was 8.92 ± 0.52 and for DA-VMAT was 8.93 ± 0.54 ($p > 0.05$).

Additional dosimetric analysis

A number of dosimetric parameters for the PTVs and OARs were analysed, and are included in Table 4. In summary, the modPTV70 had a mean $D_{95\%}$ of 70.2 ± 0.3 Gy for the IMRT plans and 70.4 ± 0.3 Gy for the DA-VMAT plans, indicating that the prescription dose for the modPTV70 was not significantly different between the groups. In addition, none of the parameters analysed was significantly different. The mean parotid

dose was kept to less than 26 Gy for 12 out of 15 cases for both IMRT and DA-VMAT, and for 3 out of 15 cases both parotids had the mean dose kept to less than 26 Gy. An example dose volume histogram for Case 15 is shown in Figure 1.

Trade-off 1: monitor units

The mean number of MUs for the IMRT plans was 711.6 ± 68.1 and for the DA-VMAT was 511.3 ± 70.5 ($p < 0.0001$).

Trade-off 2: treatment planning time

The mean optimisation times per cycle for IMRT and DA-VMAT were 6.6 ± 1.4 min and 14.7 ± 2.8 min ($p < 0.001$), the mean final dose calculation times for IMRT and DA-VMAT were 0.9 ± 0.3 min and 13.2 ± 1.4 min ($p < 0.001$), and the total optimisation and dose calculation times for a single optimisation cycle were 7.4 ± 1.5 min and 27.9 ± 3.6 min ($p < 0.001$), respectively. The total treatment planning time to create a clinically acceptable plan takes many optimisation cycles and is dependent on the planners' experience. Therefore the total planning time was not a fair metric for comparison and was not recorded.

Trade-off 3: treatment delivery time

The mean treatment delivery times for IMRT and DA-VMAT treatments were 8.3 ± 0.7 min and 3.1 ± 0.1 min ($p < 0.001$), respectively. The treatment delivery time for each IMRT and DA-VMAT plan is shown in Figure 2.

Table 4. A tabulation of the relevant dosimetric parameters and trade-offs for the 15 IMRT and 15 DA-VMAT treatment plans

Dosimetric parameter/trade-off	IMRT	DA-VMAT	p-value
modPTV70 $D_{99\%}$ (Gy)	68.1 ± 0.8	68.2 ± 0.9	NS
modPTV70 $D_{95\%}$ (Gy)	70.2 ± 0.3	70.4 ± 0.3	NS
modPTV70 D_{mean} (Gy)	73.6 ± 0.8	73.5 ± 0.9	NS
modPTV70 $D_{1\%}$ (Gy)	76.6 ± 1.5	75.7 ± 1.6	NS
modPTV70 HI ($D_{99\%}/D_{1\%}$)	0.889 ± 0.022	0.902 ± 0.026	NS
optPTV63 $D_{99\%}$ (Gy)	62.5 ± 0.8	62.7 ± 1.1	NS
optPTV63 D_{mean} (Gy)	66.9 ± 0.8	66.4 ± 0.8	NS
optPTV63 $D_{1\%}$ (Gy)	69.5 ± 1.7	70.5 ± 1.8	NS
optPTV63 HI ($D_{99\%}/D_{1\%}$)	0.888 ± 0.029	0.902 ± 0.026	NS
optPTV56 $D_{99\%}$ (Gy)	53.9 ± 1.4	54.1 ± 1.2	NS
optPTV56 D_{mean} (Gy)	60.2 ± 1.2	59.4 ± 0.9	NS
optPTV56 $D_{1\%}$ (Gy)	67.1 ± 3.6	65.2 ± 3.6	NS
optPTV56 HI ($D_{99\%}/D_{1\%}$)	0.806 ± 0.057	0.833 ± 0.055	NS
Spinal cord $D_{0.1\text{cc}}$ (Gy)	41.3 ± 2.1	41.1 ± 3.9	NS
Brainstem $D_{0.1\text{cc}}$ (Gy)	37.3 ± 12.1	36.8 ± 15.9	NS
Low dose parotid D_{mean} (Gy)	23.2 ± 6.9	24.2 ± 10.9	NS
Monitor units	711.6 ± 68.1	511.3 ± 70.5	< 0.001
Planning time per optimisation cycle (min)	6.6 ± 1.4	14.7 ± 2.8	< 0.001
Time for full 3D dose calculation (min)	0.9 ± 0.3	13.2 ± 0.4	< 0.001
Delivery time (min)	8.3 ± 0.7	3.1 ± 0.1	< 0.001
Delivery γ pass rate: $\gamma_{2\%/2\text{mm}}$ (%)	89.1 ± 3.6	90.6 ± 4.6	NS
Delivery γ pass rate: $\gamma_{3\%/3\text{mm}}$ (%)	97.4 ± 1.5	97.6 ± 1.8	NS

3D, three-dimensional; DA-VMAT, dual-arc volumetric modulated arc therapy; HI, homogeneity index; IMRT, intensity-modulated radiation therapy; modPTV70, modified planning target volume including primary tumour and involved nodes; NS, not significant; optPTV56, optimisation planning target volume including low-risk nodes; optPTV63, optimisation planning target volume including high-risk nodes.

Figure 1. A representative dose-volume histogram from the treatment plans in this study for Case 15 for intensity-modulated radiation therapy plan (solid) and dual-arc volumetric modulated arc therapy treatment plans (dashed). IMRT, intensity-modulated radiation therapy; L parotid, left parotid; modPTV70, modified planning target volume including primary tumour and involved nodes; optPTV63, optimisation planning target volume including high-risk nodes; R parotid, right parotid; VMAT, volumetric-modulated arc therapy.

Trade-off 4: treatment delivery accuracy

The treatment delivery accuracy was assessed using the gamma pass rate for thresholds of 2%/2 mm ($\gamma_{2\%/2\text{mm}}$) and 3%/3 mm ($\gamma_{3\%/3\text{mm}}$). The gamma pass rates evaluated for IMRT were $\gamma_{2\%/2\text{mm}} = 89.1 \pm 3.6\%$ and $\gamma_{3\%/3\text{mm}} = 97.4 \pm 1.5\%$, while the gamma pass rates for DA-VMAT were $\gamma_{2\%/2\text{mm}} = 90.6 \pm 4.6\%$ and $\gamma_{3\%/3\text{mm}} = 97.6 \pm 1.8\%$ ($p > 0.05$ for $\gamma_{2\%/2\text{mm}}$ and $\gamma_{3\%/3\text{mm}}$).

Trade-off 5: data requirements

The data requirements for a single IMRT and DA-VMAT dose distribution were determined to be approximately 50.4 MB and 1008 MB, respectively. For IMRT plans, the dose is stored per beam whereas with VMAT the dose is stored per control point (cp). The result is that there are 9 dose distributions for an IMRT plan and 180 (2 arcs $\times$ 90 cp arc⁻¹) dose distributions for a DA-VMAT, which explains the 20-fold increase in data.

Discussion

There were no significant differences in the dosimetric parameters; however, the parameters that tended close to

significance ($p < 0.5$) were the HI for all PTVs, $D_{1\%}$ for the modPTV70, and the D_{mean} and $D_{1\%}$ for the optPTV63 and optPTV56. These parameters are not as strictly controlled by the treatment planning goals as much as the minimum dose parameters. This study therefore supports that the homogeneity is better for DA-VMAT, which some previous studies have confirmed [9, 10, 13], while others have found the opposite to be true [12]. In addition, the mean parotid dose was reported to be higher, yet not significantly different for DA-VMAT as compared with IMRT. However, when the three cases where the planning goal was not met are removed from the analysis, the DA-VMAT plans result in a mean dose of 19.6 ± 4.4 Gy, while the IMRT plans would result in a mean dose of 20.4 ± 4.2 Gy ($p > 0.05$), which demonstrates how sensitive these values are to the three outlying cases.

It should be emphasised that the results presented in this study are specific to step-and-shoot IMRT compared with DA-VMAT optimised with Pinnacle³ and delivered using a Varian linac. It is conceivable that other planning systems, delivery systems or IMRT delivery technologies would produce different results.

In terms of plan quality, of the six previously published studies only three compared DA-VMAT with IMRT [8, 9, 12]. All three of these studies demonstrated that DA-VMAT was equivalent [12] or superior in terms of plan quality (OAR sparing and PTV coverage and homogeneity) [8, 9]. Our study demonstrates that IMRT is equivalent but not superior to DA-VMAT when the treatment plans are analysed individually or as a group.

It should be noted that the TQS metric is not perfect as binary metrics are not in line with clinical endpoints as for example the probability of myelopathy does go from 0% at 4799 cGy (*i.e.* the point when binary metric passes) to 100% at 4801 cGy (*i.e.* the point when binary metric fails).

The first trade-off investigated was MU, in which we noted a 29% decrease for DA-VMAT as compared with IMRT, which is considerably lower than the 59–68% reductions reported in previous studies; however, it is important to note the other studies utilised SW-IMRT [8, 9, 12].

The second trade-off investigated was the total treatment planning time. In this study we chose to quote the time per optimisation/dose calculation cycle, which was 7 min for IMRT and 28 min for DA-VMAT, while other studies noted the time to be 40 min per optimisation

Figure 2. A comparison of the treatment times for each of the 15 intensity-modulated radiation therapy and 15 dual-arc volumetric modulated arc therapy treatment plans. DA-VMAT, dual-arc volumetric-modulated arc therapy; IMRT, intensity-modulated radiation therapy.

cycle [9] and 1.5–2 h overall [11]. In general the DA-VMAT planning time was longer than IMRT, which contradicts what has been reported in previous studies [9, 11].

The third trade-off was the treatment time, which is one of the important benefits of DA-VMAT. In our study we found a treatment time of 3 min for DA-VMAT and 8 min for IMRT. Our results agree closely with those of Verbakel et al [9], who found that Varian linear accelerators were able to deliver DA-VMAT plans in less than 3 min and SW-IMRT plans in 8–12 min [9].

The fourth trade-off was the delivery accuracy, which was deemed to be equivalent for IMRT and DA-VMAT when considering measurements to a cylindrical array detector. This conclusion is supported for DA-VMAT measured with GafChromic film (GafChromic, Wayne, NJ) [9], single-arc VMAT measured using the Δ^4 (Scandidos AB, Uppsala, Sweden) detector [10] and two-dimensional detector array [13].

Finally, the fifth trade-off investigated the data requirements for storing the data in Pinnacle³, which were 20 times higher for DA-VMAT as compared with nine-field IMRT. This trade-off is unique to how the TPS stores dose data, and this is the first study to report this value.

Although this study has addressed many of the trade-offs encountered in comparing IMRT and DA-VMAT for an HNC population, there are many considerations that are outside of the scope of this study. First, healthcare economics should be addressed prior to a radiotherapy department implementing a new technology such as VMAT, examining all of the required costs (linear accelerator/TPS upgrade, staff training and quality assurance equipment) and person-hours (training, implementing new protocols) against expected benefits. In this study the main benefit was a decrease in treatment time from 8 min for IMRT to 3 min for DA-VMAT per HNC patient, which translates to increased throughput on the linear accelerator and less time for the patient on the treatment couch. Second, when considering secondary cancer as an end point it has been suggested that keeping the MUs lower will reduce the risk of secondary cancers [16], and in this study the MUs were reduced by 28% for the DA-VMAT plans as compared with IMRT. Third, as the treatment time increases there is an increased probability of a patient moving from their image-guided set-up position, and therefore decreased treatment time should be beneficial.

Conclusions

This study has demonstrated that the plan quality of DA-VMAT is not significantly different from nine-field step-and-shoot IMRT plans when analysing the data for the entire group or by individual case for an HNC population. With equivalence established for the treatment planning goals the trade-offs can then be explored. The trade-offs of DA-VMAT as compared with IMRT were a shorter delivery time, fewer total MUs and similar delivery accuracy. However, the DA-VMAT plans took more time per optimisation cycle and required more data storage for 3D dose information in the Pinnacle³ TPS.

The results from this study further support the use of either IMRT or VMAT for a locally HNC population with

highly refined treatment planning goals. Furthermore, the study has demonstrated that the planning and treatment of HNC patients comes with trade-offs that administrators/treating radiation oncologists must take into account when considering either IMRT or VMAT. Our clinic has begun to adapt DA-VMAT as a standard treatment for local advanced HNC.

References

1. Veldeman L, Madani I, Hulstaert F, De Meerleer G, Mareel M, De Neve W. Evidence behind use of intensity-modulated radiotherapy: a systematic review of comparative clinical studies. *Lancet Oncol* 2008;9:367–75.
2. Staffurth J, Barrett A, Barrett J, Beardmore C, Cooper T, Davies S, et al. A review of the clinical evidence for intensity-modulated radiotherapy. *Clin Oncol (R Coll Radiol)* 2010;22:643–57.
3. Chao KS, Majhail N, Huang CJ, Simpson JR, Perez CA, Haughey B, et al. Intensity-modulated radiation therapy reduces late salivary toxicity without compromising tumor control in patients with oropharyngeal carcinoma: a comparison with conventional techniques. *Radiother Oncol* 2001;61:275–80.
4. Rothschild S, Studer G, Seifert B, Huguenin P, Glanzmann C, Davis JB, et al. PET/CT with intensity modulated radiotherapy (IMRT) improves treatment outcome of locally advanced pharyngeal carcinoma: a matched-pair analysis. *Radiat Oncol* 2007;2:22.
5. Studer G, Zwahlen RA, Graetz KW, Davis BJ, Glanzmann C. IMRT in oral cavity cancer. *Radiat Oncol* 2007;2:16.
6. Otto K. Volumetric modulated arc therapy: IMRT in a single gantry arc. *Med Phys* 2009;35:310–17.
7. Bortfeld T, Webb S. Single-arc IMRT? *Phys Med Biol* 2009;54:N9–20.
8. Vanetti E, Clivio A, Nicolini G, Fogliata A, Ghosh-Laskar S, Agarwal JP, et al. Volumetric modulated arc radiotherapy for carcinomas of the oro-pharynx, hypo-pharynx and larynx: a treatment planning comparison with fixed field IMRT. *Radiother Oncol* 2009;35:464–72.
9. Verbakel WF, Cuijpers JP, Hoffmans D, Bieker M, Slotman BJ, Senan S. Volumetric intensity-modulated arc therapy vs. conventional IMRT in head-and-neck cancer: a comparative planning and dosimetric study. *Int J Radiat Oncol Biol Phys* 2009;74:252–9.
10. Bertelsen A, Hansen CR, Johansen J, Brink C. Single arc volumetric modulated arc therapy of head and neck cancer. *Radiother Oncol* 2010;95:142–8.
11. Doornaert P, Verbakel WF, Bieker M, Slotman BJ, Senan S, et al. RapidArc planning and delivery in patients with locally advanced head-and-neck cancer undergoing chemoradiotherapy. *Int J Radiat Oncol Biol Phys* 2011;79:429–35.
12. Johnston M, Clifford S, Bromley R, Back M, Oliver L, Eade T. Volumetric-modulated arc therapy in head and neck radiotherapy: a planning comparison using simultaneous integrated boost for nasopharynx and oropharynx carcinoma. *Clin Oncol (R Coll Radiol)* 2011;23:503–11.
13. Stieler F, Wolff D, Schmid H, Welzel G, Wenz F, Lohr F. A comparison of several modulated radiotherapy techniques for head and neck cancer and dosimetric validation of VMAT. *Radiother Oncol* 2011;101:388–93.
14. Phillips MH, Holdsworth C. When is better best? A multiobjective perspective. *Med Phys* 2011;38:1635–40.
15. National Cancer Institute of Canada. HN.6 clinical trial. [Cited 21 October 2011.] Available from: <http://clinicaltrials.gov/ct2/show/NCT00820248>
16. Hall EJ, Wu CS. Radiation-induced second cancers: the impact of 3D-CRT and IMRT. *Int J Radiat Oncol Phys* 2003;56:83–8.