Volumetric modulated arc therapy planning for distal oesophageal malignancies

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Objectives: Volumetric modulated arc therapy (VMAT) is a novel form of intensity-modulated radiation therapy that allows the radiation dose to be delivered in a single gantry rotation using conformal or modulated fields. The capability of VMAT to reduce heart and cord dose, while maintaining lung receiving 20 Gy <20%, was evaluated for chemoradiation for oesophageal cancer.

Methods: An optimised forward-planned four-field arrangement was compared with inverse-planned coplanar VMAT arcs with 35 control points for 10 patients with lower gastro-oesophageal tumours prescribed 54 Gy in 30 fractions. Conformal (cARC) and intensity-modulated (VMATi) arcs were considered. Plans were assessed and compared using the planning target volume (PTV) irradiated to 95% of the prescription dose (V95), volumes of lung irradiated to 20 Gy (V20), heart irradiated to 30 Gy (V30), spinal cord maximum dose and van't Riet conformation number (CN). The monitor units per fraction and delivery time were recorded for a single representative plan.

Results: VMATi provided a significant reduction in the heart V30 (31% vs 55%; $p=0.02$) with better CN (0.72 vs 0.65; $p=0.01$) than the conformal plan. The treatment delivery was 1 min 28 s for VMAT compared with 3 min 15 s.

Conclusion: For similar PTV coverage, VMATi delivers a lower dose to organs at risk than conformal plans in a shorter time, and this has warranted clinical implementation.

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Chemoradiation is an important treatment strategy in the management of oesophageal cancer in the pre-operative setting and also as a definitive therapy for locally advanced inoperable or unresectable disease [1, 2]. Locoregional disease persistence or subsequent failure is still high despite combined modality treatment. Attempts to intensify treatment, in either the chemotherapy or radiotherapy components, have been hampered by unacceptable toxicity [3–5]. However, radiation dose is an independent predictor of a pathological complete response, and the addition of chemotherapy has further impact on this aspect of outcome [6]. Improvements in local treatment delivery are therefore needed to facilitate dose escalation, as justified by radiobiological considerations [6, 7], and to minimise toxicity. The latter is especially relevant with the integration of newer treatment agents or targeted therapies in the treatment pathway.

There have been sequential improvements in tumour localisation, radiation planning and delivery over the past two decades [8]. Three-dimensional conformal radiotherapy (3DCRT) is now standard, with endoscopic ultrasound and fluorodeoxyglucose (FDG) positron emission tomography (PET) being incorporated to aid definition of tumour and the involved nodal area. Correlation

with detailed histopathological specimen analysis has provided further guidance on clinical target volume (CTV) margin definition [9].

The impact of radiation-induced heart injury in patients with oesophageal cancer is poorly documented. There are data [10] documenting clinically manifested cardiac morbidity in up to 44% of the patients, and heart irradiated to 30 Gy (V30) >46% was predictive of cardiac complications [11]. We have demonstrated a reduction in heart V40 and V45 with changes in the number and arrangement of beams in this site previously [12], using conformal planning.

Intensity-modulated radiation therapy (IMRT) allows concave dose distributions around the target volume; therefore, avoiding normal structures and offering the possibility of dose escalation. A few studies have investigated the potential dosimetric advantage of IMRT in oesophageal cancer [13–17] and have demonstrated better dose conformity to the planning target volume (PTV) and lower V20 and V30 lung volumes. One study that included in the planning goals an absolute reduction of 10% in volumes of heart receiving 40 Gy and 50 Gy described no significant reduction in cardiac dose compared with the clinical plan [13], but also indicated that in certain cases with better dose–volume histogram (DVH) objectives the heart dose could be reduced with IMRT. Sparing of the heart in terms of V30 or V45 is described with tomotherapy for oesophageal cancers [16]. Epidermal and/or vascular growth factor receptor blockade (e.g. human epidermic growth factor receptor 2 targeted therapy [18]) will probably be incorporated in

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the treatment paradigm for these patients; therefore, it is necessary to revisit radiotherapy techniques to avoid overlapping toxicities.

Further improvement on dose conformity can be achieved with volumetric intensity-modulated arc therapy (VMAT). VMAT consists of radiotherapy delivery using one or more gantry arcs with continuously varying beam aperture, gantry speed and dose rate [19, 20]. This can be thought of as an extension of intensity-modulated arc therapy as previously proposed [21]. The gantry position, collimator and multileaf collimator (MLC) leaf positions and cumulative monitor units are specified to the linear accelerator at a series of control points. The treatment planning process is required to derive a suitable prescription, such that the dose rate, gantry motion and MLC leaf motion are compatible. This is usually accomplished using some form of direct-aperture optimisation. Normally the apertures are chosen by the optimiser so that over a range of control points, covering a small range of gantry angles, an intensity-modulated fluence distribution results (VMAT_i). However, the basic variables of gantry position, MLC leaf position and cumulative monitor units can also be used to describe a simpler conformal arc (cARC), in which the aperture is shaped to the beam's eye view of the PTV at all control points, and the monitor units are chosen to optimise the dose distribution. This has advantages in terms of simplicity of optimisation, and hence ease of planning, and fast delivery time.

A number of studies indicate that, in general, VMAT provides an improved dose distribution compared with conformal or intensity-modulated techniques [20, 22–25], with a corresponding improvement in delivery efficiency. This increase in delivery efficiency occurs because the beam is continuously on throughout the treatment, as opposed to the situation with conformal or IMRT techniques, in which the beam is turned off while the gantry is moved, the wedge is inserted, or the MLC leaves are moved between segments (in the case of segmental IMRT).

The purpose of this study was to evaluate cARC techniques and intensity-modulated arc techniques for treatment of locally advanced distal oesophageal cancer. The arc plans were compared with clinically optimised conformal four-field plans as a conformal four-field plan is the current standard practice both at this centre and elsewhere. IMRT techniques have been investigated previously [13–17], so are not considered here. The aim was to reduce heart and spinal cord dose, while maintaining lung receiving 20 Gy <20% and PTV coverage by 95% prescription isodose.

Methods and materials

Patients and contouring

CT data sets from 10 patients treated radically for locally advanced or inoperable cancer of the lower third of the oesophagus or the oesophageal junction were retrospectively studied in an ethics and research board-approved protocol (Table 1).

According to the departmental protocol, patients were positioned supine, with their arms above their head on a

chest board, and immobilised with knee and ankle support. A free breathing helical planning CT scan was acquired using either a HiSpeed QXi multislice CT scanner (GE, Fairfield, CT) (until December 2007) or (subsequently) a Brilliance large-bore CT scanner (Philips Medical Systems, Cleveland, OH). A helical planning CT was obtained using 2.5 mm or 3 mm slices.

The volumes were delineated by the treating physician on the axial images of the planning CT using Pinnacle3 planning software (Philips Medical Systems, Madison, WI) v.8.0h. The gross tumour volume (GTV), including the gross tumour and involved nodes as defined by diagnostic CT, oesophagogastrosocopy, endoscopic ultrasound and PET scan, was outlined. The CTV was created by manually contouring the oesophagus for 3–5 cm superiorly and inferiorly to the GTV then adding 0.5 cm circumferentially to the created volume to account for microscopic spread. For the planning target volume, a 1.0 cm margin in all directions was added to the CTV. The following organs at risk were contoured: lungs (total lung), heart, spinal cord, liver and kidneys. All contours were reviewed and edited by the same physician (DMT).

Conventional planning

A forward-optimised four-field plan was designed to ensure PTV coverage by the 95% isodose in accordance with International Committee on Radiation Units and Measurements (ICRU) 50/62 recommendations, while maintaining cord organs at risk (OAR) constraints. The plans consisted of a four-field box arrangement, with the anterior and posterior beams more heavily weighted than the lateral beams. This is the standard technique in our institution, and we have demonstrated that the heart dose is reduced with this technique [12]. A 5 mm margin between the most intrusive corner of the MLC leaves and the PTV was allowed, with an additional 4 mm superiorly and inferiorly. The main constraint was to limit the spinal cord maximum dose to less than 45 Gy. The plans were optimised by allowing the spinal cord dose to rise as required, in order to minimise the other OAR doses subject to the tolerance dose, principally the lung V20 <20%. A combination of 6 MV and 10 MV beams was used in all studied cases. The dose calculation algorithm was collapsed cone convolution with interpolation in regions of low-dose gradient (adaptive convolution) using Pinnacle3 planning software v.8.0h. CT-based pixel-by-pixel inhomogeneity correction was used and the dose grid resolution was 0.25 × 0.25 × 0.25 cm. The dose distributions in the PTV and OAR were evaluated using DVH. A total dose of 54 Gy in 1.8 Gy per fraction for 30 daily fractions was prescribed to the ICRU reference point concurrent with chemotherapy. All patients were treated with this plan.

VMAT planning

The patients were planned using AutoBeam v.4.7 in-house software [26]. The dose prescribed for VMAT planning was as per the clinical plan, with objectives and constraints for inverse planning described in Table 2.

Table 1. Patient and tumour characteristics

Patient no.	Tumour location	TNM stage	GTV length (cm)	PTV volumes (ml)
1	OGJ	T3N1M0	8.75	339
2	Lower one-third	T3N1M0	6.2	534
3	OGJ	T3N1M0	6.5	284
4	OGJ	T3N1M0	5.25	384
5	Lower one-third	T3N0M0	8.4	349
6	OGJ	T3N1M0	5.8	427
7	OGJ	T3N1M0	7.2	705
8	Lower one-third	T2N0M0	3.1	205
9	Lower one-third	T4N1M0	5.4	453
10	Lower one-third	T3N1M0	8.2	306

GTV, gross tumour volume; OGJ, oesophageal junction; PTV, planning target volume.

The constraints referred to limits which were given top priority in the optimisation. When these constraints were met, no further optimisation took place for those variables. In the event that a constraint could not be met, the optimiser selected the closest that could be achieved and continued to optimise the objectives [22]. The optimisation engine worked most effectively when supplied with simple goals, so V20 was used for the lung irradiated volume, although V5, V10 and mean dose were also of interest in the study (see below). Experience showed that, by choosing the mean heart dose for optimisation, it was possible to reduce the high-dose volumes of clinical relevance (>30 Gy) received by the heart. A single 6 MV coplanar clockwise arc starting at gantry angle 190° and finishing at gantry angle 170° was defined. The arc consisted of 35 control points at 10° gantry intervals. The collimator angle was fixed at 5° throughout the arc to minimise the effects of interleaf leakage and tongue-and-groove effect.

Two VMAT plans were created: one with cARC and the second one with intensity modulation (VMATi). For cARC, the MLC leaves conformed to the beam's eye view of the PTV, with the aperture size defined as the edge of the PTV plus a 0.5 cm margin (0.9 cm superiorly and inferiorly) to the nearest corner of the MLC leaf. The control point weights were optimised using fast simulated annealing.

The VMATi plan additionally allowed intensity modulation by optimising the MLC leaf and jaw settings for each control point of the arc. The maximum allowed aperture size was equal to a conformal aperture, the minimum allowed aperture width or length was 2.5 cm and the minimum equivalent square aperture size was 3 cm. The MLC movement between control points was limited to allow the gantry to rotate at close to maximum speed of 6° s^{-1} . The accelerator was able to deliver plans with more leaf motion, but this motion was not

considered necessary in this case and a limited leaf motion, with consequent fast delivery time, was used instead. To produce the control point apertures, AutoBeam performed a fluence optimisation using iterative least squares [27] followed by a segmentation, and then a direct-aperture optimisation with constrained leaf positions [28]. Control point weights were optimised using fast simulated annealing [28]. These processes used an objective function which gave priority to the constraints, but also simultaneously optimised the objectives [22]. Dose grid resolution was $0.4 \times 0.4 \times 0.4$ cm for the inverse planning.

The plan prescription, including the MLC leaf sequence, was sent directly from AutoBeam to Mosaic v.1.41 (Impac Medical Systems, Inc., Sunnyvale, CA) by digital imaging and communication in medicine (DICOM) transfer, for delivery on a Precise accelerator with an MLCi multileaf collimator (Elekta Ltd, Crawley, UK). In addition, in order to visualise the dose distribution with as accurate a dose calculation as possible, an automatic script was used to transfer both the cARC and VMATi plans to Pinnacle3 v.8.0h for recalculation on a $0.25 \times 0.25 \times 0.25$ cm grid. AutoBeam used a fast convolution dose algorithm [29] and Pinnacle3 used a slower, but slightly more accurate, collapsed cone convolution algorithm, so recalculation of the plans in Pinnacle3 was performed to obtain the greatest possible dose accuracy. The differences between doses calculated by AutoBeam and Pinnacle3 were of the order of 2–3% [29], with the change in dose grid resolution known to have a negligible impact for this treatment site. Similar agreement of 2–3% was obtained when verifying the delivered dose against Pinnacle3 calculations [30]. The small differences in dose were resolved by renormalising the plan in Pinnacle3. Pinnacle3 was used for all dosimetric reporting included in this study. The dose calculation algorithm was collapsed cone convolution with interpolation in regions of

Table 2. Objective and constraints for volumetric modulated arc therapy planning

Objectives	Minimise RMS dose around PTV	54 Gy	Weight 100
	Minimise PTV volume irradiated to	57 Gy	Weight 20
	Maximise PTV volume irradiated to	51 Gy	Weight 20
Constraints	Spinal cord	Maximum dose	<45 Gy
	Lungs	V20	$<20\%$
	Liver	V30	$<30\%$
	Heart	Mean dose	<25 Gy
	PTV	Maximum dose	<58 Gy

PTV, planning target volume; RMS, root-mean-square deviation (to improve homogeneity in the PTV).

low-dose gradient (adaptive convolution). CT-based pixel-by-pixel inhomogeneity correction was used. Pinnacle3 v.8.0h was not designed to handle VMAT beams, so the beams were created as static beams. Each control point was represented as a discrete beam and the motion of the MLC between successive control points was represented by 10 interpolated apertures within that beam [22]. Although the 10 interpolated apertures were at the same gantry angle (rather than having interpolated gantry angles), it has been shown that the error introduced by this approximation is minimal (<1%) [31]. The plans were normalised to the ICRU reference or a similar point near to the centre of the PTV, as recommended in ICRU 50 [32] and ICRU 62 [33]. Note that the use of AutoBeam and the subsequent transfer to Pinnacle3 will not be necessary when the next release of Pinnacle3 (v.9) is available [23], as the integral SmartArc software can be used. Time for delivery was recorded as the time taken from the start of the first beam to the end of the last beam for a single representative plan.

Plans analysis and comparison

The evaluations of plans were performed by means of DVHs. For the PTV, the 95% isodose coverage and maximum point dose were measured. To assess plan quality with respect to the dose delivered to the tumour, the van't Riet conformation number (CN) was used [34, 35]. This is defined as follows:

$$CN = \frac{TV_{ri}}{TV} \times \frac{TV_{ri}}{V_{ri}} \quad (1)$$

where TV_{ri} is the target volume covered by the reference isodose (95% for this case), TV is the target volume (PTV) and V_{ri} is the total volume encompassed by the reference isodose. The CN ranges from 0 to 1, where 1 is the ideal value. A value close to 0 indicates either total absence of conformation, *i.e.* the target volume is not irradiated, or a very large volume of irradiation compared with the target volume.

The following dosimetric indices were calculated to assess the effects of both VMAT techniques on normal tissue irradiation: volumes of lung irradiated to 5 Gy, 10 Gy and 20 Gy (V_5 , V_{10} and V_{20} , respectively) and mean lung dose; heart irradiation, V_{30} , V_{35} , V_{40} and mean heart dose; spinal cord, maximum point dose; and liver, V_{30} and mean liver dose. The acceptable clinical constraints for normal tissues are described in Table 2 and represent accepted metrics [36]. The investigated population means and ranges are reported.

The two-sided Wilcoxon matched pairs signed rank test was applied to the described parameters and the threshold for statistical significance was set for $p < 0.05$.

Results

Dose calculations and target coverage

All types of plans satisfy the clinical constraints for normal tissues. The VMAT optimisation (computation time only) is faster for cARC than for VMATi, taking

around 15 min rather than about 2 h. One run of the optimisation algorithm is sufficient for all plans for all patients once the objectives and the constraints are defined. This is in contrast to many other optimisation algorithms that require multiple runs to be carried out for different settings of importance factors and other parameters. The isodose distributions of the clinical plan and the VMATi plan for one of the typical cases evaluated is presented in Figure 1. Table 3 represents more detailed results of the PTV coverage and OAR doses. The mean (range) PTV95% coverage was 98% (94–100%) for the clinical plan, 87% (48–98%) for cARC and 92% (62–100%) for VMATi. The mean (range) of the maximum point dose received by the PTV was 57.7 Gy (56.7–59.7 Gy) for the clinical plan, 57.7 Gy (54.8–59.9 Gy) for cARC and 56.5 Gy (55.0–58.4 Gy) for VMATi.

Organs at risk

Lungs

For both cARC and VMATi plans, the volumes of lung that received a low dose were significantly higher for the V_5 and V_{10} ; however, V_{20} and mean lung dose were similar (Table 3). Figure 2a depicts individual lung V_{20} doses for all the patients studied. VMATi appeared to deliver usually lower lung doses than cARC for all volumes investigated. The desired lung organ constraints were not always met; however, the variation was within accepted clinical tolerance.

Heart

The volume of irradiated heart was significantly reduced with the VMAT approach (Table 3); VMATi had the greater impact, especially at doses that correlated with increased cardiac toxicity (Figure 2b). At V_{30} and V_{35} a reduction of $\geq 22\%$ in irradiated volumes was seen with both VMAT plans; at V_{40} , VMATi provided 10% and cARC 6% reduction.

Spinal cord

The spinal cord had a reduced maximum point dose: from 35.8 Gy for the clinical plan *vs* 29.0 Gy ($p = 0.08$) and 29.4 Gy ($p = 0.04$) for cARC and VMATi, respectively.

Liver

All plans met the constraints (Table 3), as described by mean liver dose and V_{30} .

Delivery times

A clinical plan takes 3 min 15 s to deliver, whereas the cARC plan takes 1 min 6 s to deliver and a VMATi plan takes 1 min 28 s to deliver, for a representative case with an average size PTV.

Discussion

This study reports a comparison of volumetric modulated arc therapy with 3DCRT for radical treatment of distal oesophageal cancers. Given the relatively

(a)

(b)

Figure 1. Patient 9. (a) Planning target volume (purple) coverage in axial and coronal planes for clinical plan (left panel), cARC plan (middle panel) and VMATi (right panel) isodoses. Red, 100%; green, 95%; purple, 70%; blue, 50%; yellow, 30%. (b) Dose-volume histograms. Dashed lines, clinical plan; solid lines, cARC (left panel), VMATi (right panel). Black, planning target volume; red, heart; blue, lungs; green, spinal cord.

limited experience reported with IMRT in this tumour site, we are of the opinion that this study should be relevant to current clinical practice. With the exception of one clinical series that used IMRT to treat cervical oesophagus primaries [37], most data have been limited to dosimetric analyses. The current study reveals that VMAT is a conformal and efficient technique to treat oesophageal cancer. The rapid delivery of treatment is an advantage with a single arc delivery of 1.8 Gy of about 60–90 s for a representative case. The obvious advantage to this is a possible reduction in intrafraction motion and opportunity for gating. The efficient delivery can also increase the number of fractions delivered per linear

accelerator per day. Delivery speed may be offset somewhat by an increased set-up and quality assurance time for a more complex technique. However, in this centre, the time for set-up and imaging for a VMAT treatment is the same as for a conformal fixed-field plan, so the speed of the VMAT delivery contributes directly to the patient throughput.

An explanation for the poor PTV coverage is the overlap between the lungs and PTV and the use of a convolution superposition calculation algorithm with heterogeneity correction. This affects both the conventional and arcing techniques to some extent. In the case of the arcing techniques, cARC does not have the facility

Table 3. Mean and range for cARC and VMATi in relation to the clinical plan

	Clinical plan	cARC	p-value ^a	VMATi	p-value ^b
PTV 95% coverage (%)	98 (94–100)	87 (48–98)	0.002	92 (62–100)	0.37
CN	0.65 (0.59–0.70)	0.56 (0.29–0.80)	0.1	0.72 (0.61–0.84)	0.01
Lung V5 (%)	36 (22–59)	52 (39–85)	0.003	51 (38–84)	0.003
Lung V10 (%)	26 (16–46)	43 (27–77)	0.002	40 (26–70)	0.002
Lung V20 (%)	15 (6–24)	17 (7–23)	0.16	15 (9–23)	0.76
Mean lung dose (Gy)	8.2 (5.4–13.4)	10.7 (7.2–16.4)	0.007	9.7 (6.8–15.0)	0.02
Heart V30 (%)	55 (32–71)	33 (21–54)	0.02	31 (24–38)	0.039
Heart V35 (%)	44 (25–60)	26 (15–44)	0.03	22 (15–28)	0.002
Heart V40 (%)	26 (11–48)	20 (10–36)	0.2	16 (9–21)	0.007
Mean heart dose (Gy)	28.4 (23.9–32.9)	27.3 (23.9–33.5)	0.3	25.9 (24.0–27.5)	0.04
Liver V30 (%)	17 (4–39)	14 (3–28)	0.4	17 (3–28)	0.1
Mean liver dose (Gy)	16.1 (7.1–24.3)	15.8 (5.5–25.0)	0.8	16.0 (5.8–23.5)	0.7
Maximum cord dose (Gy)	35.8 (17.8–44.2)	29.0 (19.1–42.3)	0.08	29.4 (21.7–38.7)	0.4
MU	320 (242–473)	245 (221–275)	0.02	260 (223–282)	0.08

cARC, conformal arc therapy; CN, conformation number; MU, monitor units; PTV, planning target volume; V, volume; VMATi, volumetric intensity modulated arc therapy.

^ap-value compares clinical plan with cARC.

^bp-value compares clinical plan with VMATi.

to introduce a wedge effect, so the PTV coverage is lower than for the clinical plan. With cARC, the monitor units delivered at each control point vary, but not the fluence profile. It is therefore possible to use the depth dose characteristics of the beam to control the dose to some degree in the transaxial plane but not in the superior–inferior direction. Use of a physical wedge is not technically feasible in the delivery system. An additional arc is a possibility, but the number of monitor units required for this would be very low, so this is not very feasible. For VMATi, the inverse planning method introduces smaller segments to facilitate wedging effects, so the PTV coverage is somewhat improved compared with cARC. Because of the very different dose distributions produced by the conventional and arcing plans, it is also difficult to normalise the plans with exact equivalence, and it is likely that this accounts for some of the difference in PTV coverage between the conventional and arcing plans. Any remaining differences in PTV coverage are attributed to the limitations of the inverse planning software used for the arcing plans.

The average number of monitor units is reduced by 24% with cARC and by 19% with VMATi when compared with the clinical plan. The wedge factor of the 53°

wedge used for the conventional plans is approximately 0.25, so that to deliver a given isocentric dose requires 4 times as many monitor units with the wedge in place as without it. Thus, the VMAT plans, where wedges are not used, require fewer monitor units, as checked by multiplying out the wedge factor in the clinical plans. Note that other manufacturers' wedges may have a different wedge factor from that of the Elekta motorised wedge, so that the gain in monitor unit efficiency may not be the same as in this study. Other studies using RapidArc (Varian Medical Systems, Palo Alto, CA) do not show such a reduction in monitor units, for example that by Vanetti et al [24]. This is thought to be because the oesophagus is a simpler volume to treat, so that it requires fewer small apertures which irradiate only part of the PTV at one time. Moreover, AutoBeam generally produces a higher proportion of conformal apertures which irradiate most or all of the PTV at one time. Although AutoBeam is a specific in-house program [28], it produces similar apertures and numbers of monitor units to those produced by other treatment planning systems that operate in conjunction with the Elekta VMAT. The number of monitor units used by the arcing plans is not a major advantage, but it should reduce the

Figure 2. Case-by-case comparison of lung V20 (a) and heart V30 (b) for the three types of treatment plans. Grey, clinical; white, cARC; black, VMATi.

scattered dose to the whole patient, thereby reducing the risk of secondary malignancies.

VMATi plans offered the best solution, not only in terms of adequate PTV coverage and OAR sparing but also in terms of conformity of treatment, compared with the 3DCRT plan, with less scattered dose to the patient. The other advantage of this technique is the single optimisation needed to obtain an acceptable solution. Unlike some optimisation techniques, it is not necessary to adjust importance factors or constraints and re-run the optimisation repeatedly.

The present study considers VMAT in comparison with a conformal fixed-field technique, in view of the widespread use of the conformal technique in standard practice. Comparing VMAT with IMRT for other treatment sites generally shows a small improvement in dose distribution, a reduction in monitor units and a significantly shorter treatment time (*e.g.* Vanetti et al [24]). Similar results are expected to hold with respect to the oesophagus. However, most centres are still using conformal techniques for treatment of the oesophagus, and, with arcing techniques being ideally suited to treatment of the approximately cylindrical target volume, it is likely that many centres will wish to shift their practice directly from conformal fixed-field techniques to arc techniques.

Oesophageal IMRT studies have concentrated on lung dose reduction with improved target conformality [13–15]. In the current series we have attempted to keep the dose delivered low to all surrounding critical structures. There is a reduction in the maximum cord dose with both VMAT techniques to a mean value for the studied patients of 29 Gy. The decrease in cord dose could also be explained by the use of arcing as a planning technique even though no constraints have been placed on the numbers of monitor units delivered by each control point. The cord dose described in other studies is: 42 Gy [13]; 41 Gy [16]. The reduction in cord dose could be of significance, as new evidence suggests that cord dose should not exceed 40 Gy in cases of combined modality with oxaliplatin [38, 39].

With both arc techniques, the mean lung dose and V20 are within clinically accepted tolerance [40]; however, emerging data suggests that the percentage of lung volume receiving lower doses may also be predictive of pulmonary toxicity. The mean lung dose for the clinical plan is significantly lower than for the other techniques. Lee et al [41] reported that, in patients receiving surgery following chemoradiation (median dose 45 Gy), the pulmonary complications increased significantly when V10 exceeded 40%. In the current study the mean V10 is 43% (range 27–77%) and 40% (range 26–70%) with cARC and VMATi, respectively. The only predictor of toxicity not met with the VMAT technique is V5. The studied population mean V5 for VMATi is 51% (range 38–84%). This appears to be slightly lower than the values described by Mayo et al [14]: mean $56.5 \pm 17\%$ (for 4-field IMRT) and $67.4 \pm 17\%$ (for 9-field IMRT); and those described by Chandra et al [13]: median 58.6% (for 4-field IMRT) and 68.3% (for 9-field IMRT). Therefore, this technique appears to have V5 doses at a similar level to those demonstrated by IMRT. The overall increases in lung dose seen using these techniques might be of concern if surgery was part of overall management.

Long-term cardiac morbidity and mortality from oesophageal radiation remains largely unknown, given the limited life expectancy of the patients with advanced oesophageal cancer, and reduction of heart dose has not been investigated in clinical studies. Although it may be difficult to demonstrate in patients with oesophageal cancer, it is likely that patients who are long-term survivors may see an increased risk of cardiac events, as seen in breast cancer [42] and lymphoma [43]. Tripp et al [44] have investigated changes in ejection fraction using multiple-gated acquisition cardiac scans before and after receipt of concurrent chemoradiation for oesophageal malignancies. They have demonstrated a statistically significant reduction, but of no clinical significance, in median post-chemoradiation ejection fraction (59% to 54%; $p=0.01$). V30 >46% was described [11] as a predictor of development of pericardial effusion for patients receiving chemoradiation of inoperable oesophageal malignancies. In the current study, VMATi reduces V30 by 24% to $31 \pm 4\%$ [1 standard deviation (SD)] and V40 by 10% to $16 \pm 4\%$ (1 SD) when compared with the clinical plan. There is no significant reduction with cARC plans for V40%. The same magnitude of reduction in cardiac doses has not been illustrated by other studies, such as Chandra et al [13], who found no significant change when attempting to reduce heart dose, whereas Mayo et al [14] described V30 of >55% for hybrid IMRT and conventional plans but did not specifically attempt to reduce heart dose. Helical tomotherapy has also been described to reduce the volume of heart irradiated in this tumour site [16].

An obvious concern with rapidly changing dose gradients is the possibility of a geometrical miss during radiotherapy delivery; nevertheless, set-up variation can be assessed using three-dimensional volumetric imaging for either generic set-up error prescription [45] or defining patient-specific volumes, and should be available for treatment verification. At the present time, VMAT can be delivered on a conventional linear accelerator using a conventional MLC. Therefore, robust and reproducible treatment planning methods, *i.e.* those which provide simple, deliverable treatment plans with a minimum of dosimetric iterations, need to be found with the current planning technology to facilitate clinical implementation of this technique. The implications of increasing the numbers of VMAT deliveries would not only be of economical magnitude, such as greater machine throughput without the need to acquire a new machine, but also possible improved clinical outcomes as predicted by other treatment planning studies.

Conclusion

The results of this study have demonstrated that VMAT is able to provide highly conformal plans with significant sparing of the organs at risk and adequate PTV coverage for lower oesophageal cancers. VMATi offers the dual advantages of rapid rotational delivery and dosimetric intensity modulation.

The possibility of radiotherapy dose escalation could be revisited again as target definition and normal tissue sparing are facilitated by new imaging and planning techniques, including VMAT.

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