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Original article

Evaluation of unified intensity-modulated arc therapy for the radiotherapy of head-and-neck cancer

Michael MacFarlane [a,b,*], Douglas A. Hoover [a,b,c], Eugene Wong [a,c,d], Nancy Read [b,c], David Palma [a,b,c], Varagur Venkatesan [b,c], Alex Hammond [b,c], Jerry J. Battista [a,b,c], Jeff Z. Chen [a,b,c]

[a] Department of Medical Biophysics, Western University; [b] London Regional Cancer Program, London Health Science Center; [c] Department of Oncology, Western University; and [d] Department of Physics & Astronomy, Western University, London, Canada

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ABSTRACT

Purpose: Recently our group developed a unified intensity-modulated arc therapy (UIMAT) technique which allows for the simultaneous inverse-optimization and the combined delivery of volume-modulated arc therapy (VMAT) and intensity-modulated radiation therapy (IMRT). The aim of this study was to evaluate the dosimetric benefits of UIMAT plans for radiation treatment of complex head-and-neck cancer cases.

Methods and materials: A retrospective treatment planning study was performed on 30 head-and-neck cases, 15 of which were treated clinically with VMAT while the other 15 were treated with step-and-shoot IMRT. These cases were re-planned using our UIMAT technique and the results were compared with the clinically delivered plans. Plans were assessed in terms of clinically relevant metrics describing target volume coverage, dose conformity, and the sparing of organs at risk.

Results: When compared to stand-alone VMAT or IMRT, UIMAT plans offered slightly better tumor volume coverage (Median D95: 98.1% vs. 97.5%, $p = 0.01$) and similar dose conformity (Median CI: 0.69 vs. 0.69, $p = 0.09$). More significantly, UIMAT plans had substantially lower doses to all organs at risk, including the spinal cord (Median $D_{2\%}$: 29.9 Gy vs. 35.6 Gy, $p < 0.01$), brainstem (Median $D_{2\%}$: 21.2 Gy vs. 25.6 Gy, $p < 0.01$), left parotid (Median D_{Mean}: 26.1 Gy vs. 28.0 Gy, $p < 0.01$), and right parotid (Median D_{Mean}: 23.6 Gy vs. 27.2 Gy, $p < 0.01$). The reduction in OAR doses did not result from the redistribution of dose to unspecified tissue. Furthermore, UIMAT plans can be delivered with comparable delivery times to VMAT (Median time: 135 s vs. 168 s, $p = 0.394$) but with fewer monitor units (Median MU: 486 vs. 635, $p < 0.01$).

Conclusions: Compared to stand-alone IMRT or VMAT, UIMAT was demonstrated to have a dosimetric advantage for the radiation treatment of head-and-neck cancer.

Volume-modulated arc therapy (VMAT) and fixed-gantry intensity-modulated radiation therapy (IMRT) are two commonly used external beam radiotherapy techniques for the treatment of cancers. Although these two delivery modalities are often treated in practice and literature as disparate or competing techniques, they are in fact both mechanically and dosimetrically complementary to each another.

The fixed-angle delivery used in IMRT allows for the creation of steep dose gradients at the field edges and highly modulated intensity patterns from each beam direction. With the wise selection of beam orientations, substantial sparing of select organs at risk (OAR) is possible with this technique [1,2]. However, for more rotationally symmetric target volumes, a larger number of beams may be required to achieve sufficient dose coverage and conformity while still sparing the surrounding OARs, resulting in reduced delivery efficiency. In such cases, the rotational delivery of VMAT is preferred as the wide range of deliverable angles can create very conformal dose distributions in a timely and efficient manner [3–7]. However, the requirements of continuous gantry motion and high delivery efficiency limit the degree of intensity modulation achievable at any given beam angle.

Many groups have demonstrated that the combination of IMRT and VMAT within a single plan provides a therapeutic advantage over treatments using either IMRT or VMAT alone, as it utilizes the dosimetric advantages of both techniques [8–13]. This could be particularly advantageous in complex sites such as the head and neck where, in general, no consistent dosimetric advantage is observed between VMAT and IMRT [14]. It should be noted that

* Corresponding author at: London Regional Cancer Program: Room A1-119, 790 Commissioners Road East, London, Ontario N6A 4L6, Canada.
E-mail address: mmacfar4@uwo.ca (M. MacFarlane).

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with these previous hybrid techniques, IMRT and VMAT have not been fully integrated during either the inverse-optimization or beam delivery process.

Recently, our group proposed a method called unified intensity-modulated arc therapy (UIMAT) which permits the simultaneous inverse optimization and concurrent delivery of VMAT and IMRT in a single arc [15]. Specifically, during the arc delivery, the gantry rotation can be reduced to a near-stop in order to deliver IMRT beam segments at opportune gantry angles. This current study evaluates the potential benefit of UIMAT for the radiotherapy of complex head-and-neck cancer, compared to strictly VMAT or IMRT. This site was selected based on promising preliminary results obtained in a previous feasibility study [15].

Methods and materials

Thirty previously treated head-and-neck cases were arbitrarily selected for this study. Fifteen of these cases were treated with dual-arc VMAT while the other fifteen cases were treated with a variable number of step-and-shoot (SS) IMRT beams. No factors related to the patient, primary disease site, or the prescribed dose was considered during the selection. A summary of the selected cases is provided in Supplementary Table 1 (available online at www.thegreenjournal.com).

UIMAT plans were generated for each patient using custom scripts developed for Pinnacle[3] v9.6 Radiation Therapy Planning System (Philips Healthcare, Fitchburg, USA). Technical details of the UIMAT method were previously described by Hoover et al. [15]; however, the method can be roughly divided into five stages:

(1) Fluence optimization: multiple static beams are evenly distributed along the arc range and their fluences are optimized.
(2) MLC sequencing: optimized fluences are converted into deliverable MLC segments.
(3) UIMAT sequencing (re-assignment): deliverable beams are sequenced via a script into VMAT or IMRT phases based on the number of MLC segments in a beam. Beams with fewer segments are converted to VMAT phases, while beams with more segments are converted to IMRT phases with near-constant gantry angles as shown in Fig. 1.
(4) Direct Aperture Optimization (DAO): both VMAT and IMRT phases are optimized simultaneously using Pinnacle's DAO algorithm.
(5) Unification: the optimized VMAT and IMRT phases, which are treated as separate beams within Pinnacle, are merged by script into a single UIMAT arc for final dose calculation and delivery.

All UIMAT plans were created by a single planner (MM) and treatment planning times were recorded. Planning objectives for each UIMAT plan were copied from the clinical plan and set so that 95% of the planning target volume (PTV) would receive at least 95% of the prescription dose, while OAR doses were kept as low as achievable. Without exception, all OAR doses in both clinical and UIMAT plan were kept below our institutional standards, which originate from recommendations by RTOG clinical trials (RTOG 0225, 0513, 0522, 0615, and 0619), and QUANTEC guidelines [16].

UIMAT plans were optimized using the same (or very similar) objectives as the clinical plans. OAR objectives were set to reduce global OAR doses as opposed to the dose to any specific endpoint. Individual dose objectives were made more stringent if their relative contribution to the total objective function approached zero. In this way, the dose to all OARs was pushed as low as possible, in an unbiased manner. No explicit attempt was made to surpass the clinical plan; rather, UIMAT optimization was continued until the plan reached its highest potential. This is similar to how our clinical cases are planned.

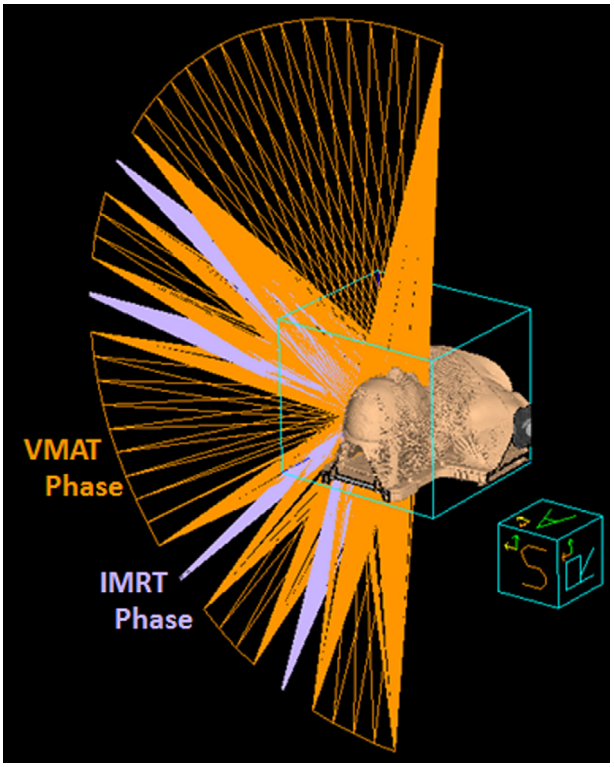

Fig. 1. Illustration showing IMRT phases (lavender) and VMAT phases (orange) generated by the UIMAT script. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The completed UIMAT plans were then evaluated against the clinically delivered plans in terms of target volume coverage, conformity index (CI), as well as clinically relevant OAR dose metrics. Wilcoxon signed rank tests were performed in SPSS (IBM Corp., Armonk, USA) to test for statistically significant differences between the UIMAT plans and the clinically delivered plans. The threshold for statistical significance was set to 5%. For plans with multiple PTVs (each having a different dose level), the average of a PTV metric was used in the analysis. For instance, if a plan had a PTV_{70Gy} with a mean dose of 102% (relative to 70 Gy), and a PTV_{56Gy} with a mean dose of 110% (relative to 56 Gy), then the PTV mean dose used in the analysis would be 106%.

The conformity index used here is similar to the one introduced by Oozeer et al. [17]:

$$\begin{aligned} CI &= (\text{cover factor}) \times (\text{spill factor}) \\ &= \left(\frac{V_{95}(\text{PTV})}{V_{\text{PTV}}}\right) \times \left(\frac{V_{95}(\text{PTV})}{V_{95}(\text{body})}\right) \end{aligned} \quad (1)$$

where V_{95}(PTV) and V_{95}(body) are the volumes of the PTV and body, respectively, receiving at least 95% of the prescription dose, and V_{PTV} is the volume of the PTV. This equation was defined initially for a single dose level. To handle the case where multiple dose levels exist, the PTV volume with a lower prescription dose will also include all higher dose PTV volumes. For example, for a plan with PTV_{70Gy}, PTV_{63Gy}, and PTV_{56Gy}, to calculate the conformity index for the PTV with the lowest prescription dose (56 Gy), the PTV in Eq. (1) will be the union of the three PTV volumes.

Treatment plans were validated with an ArcCheck phantom (Sun Nuclear Corp., Melbourne, USA), using a TrueBeam linear accelerator (Varian Medical Systems, Palo Alto, USA) operating in

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