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Multi-institutional comparison of simulated treatment delivery errors in ssIMRT, manually planned VMAT and autoplan-VMAT plans for nasopharyngeal radiotherapy

Elise M. Pogson [a,b,c,*], Sankar Aruguman [b,c], Christian R. Hansen [d,e], Michael Currie [f], Bradley M. Oborn [f,g], Samuel J. Blake [a,c], Josip Juresic [b], Cesar Ochoa [b], Jim Yakobi [b], Alicia Haman [b], Admir Trtovac [b], Martin Carolan [f], Lois Holloway [a,b,c,g,h], David I. Thwaites [a]

[a] Institute of Medical Physics, School of Physics, University of Sydney, Sydney 2006, Australia
[b] Liverpool and Macarthur Cancer Therapy Centres, Liverpool 2170, Australia
[c] Ingham Institute for Applied Medical Research, Sydney 2170, Australia
[d] Laboratory of Radiation Physics, Odense University Hospital, 5000, Denmark
[e] Institute of Clinical Research, University of Southern Denmark, 5000, Denmark
[f] Illawarra Cancer Care Center, Wollongong 2500, Australia
[g] University of Wollongong, Wollongong 2500, Australia
[h] South Western Sydney Clinical School, University of New South Wales, Sydney 2170, Australia

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ABSTRACT

Purpose: To quantify the impact of simulated errors for nasopharynx radiotherapy across multiple institutions and planning techniques (auto-plan generated Volumetric Modulated Arc Therapy (ap-VMAT), manually planned VMAT (mp-VMAT) and manually planned step and shoot Intensity Modulated Radiation Therapy (mp-ssIMRT)).

Methods: Ten patients were retrospectively planned with VMAT according to three institution's protocols. Within one institution two further treatment plans were generated using differing treatment planning techniques. This resulted in mp-ssIMRT, mp-VMAT, and ap-VMAT plans. Introduced treatment errors included Multi Leaf Collimator (MLC) shifts, MLC field size (MLCfs), gantry and collimator errors. A change of more than 5% in most selected dose metrics was considered to have potential clinical impact. The original patient plan total Monitor Units (MUs) were correlated to the total number of dose metrics exceeded.

Results: The impact of different errors was consistent, with ap-VMAT plans (two institutions) showing larger dose deviations than mp-VMAT created plans (one institution). Across all institutions' VMAT plans the significant errors included; ±5° for the collimator angle, ±5 mm for the MLC shift and +1, ±2 and ±5 mm for the MLC field size. The total number of dose metrics exceeding tolerance was positively correlated to the VMAT total plan MUs ($r = 0.51$, $p < 0.001$), across all institutions and techniques.

Conclusions: Differences in VMAT robustness to simulated errors across institutions occurred due to planning method differences. Whilst ap-VMAT was most sensitive to MLC errors, it also produced the best quality treatment plans. Mp-ssIMRT was most robust to errors. Higher VMAT treatment plan complexity led to less robust plans.

1. Introduction

Intensity modulated radiotherapy (IMRT) has been applied extensively to head and neck cancers, due to its ability to sculpt dose and thereby achieve conformal doses to the targets whilst minimizing dose to organs at risk [1]. IMRT typically consists of 5–7 radiation fields at differing gantry angles, with each field made up of multiple shapes and segments. Volumetric modulated arc therapy (VMAT) has been shown to enable more efficient treatment delivery compared to IMRT [2,3]. However, the complexity of plans and increased modulation has been shown to feature small open segments surrounded by large areas of the beam only

* Corresponding author at: A28 – School of Physics, Institute of Medical Physics, The University of Sydney, Sydney 2006, Australia.
E-mail address: elise.pogson@sydney.edu.au (E.M. Pogson).

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shielded by the MLC, meaning careful MLC transmission modelling is essential for accurate overall modelling of treatments such as VMAT [4,5]. Both of these techniques (IMRT and VMAT) produce highly conformal dose distributions to the targets and rely heavily on multiple machine parameters, including MLC mechanical features, to be accurate [6]. VMAT sensitivity to errors in treatment delivery has been shown to be similar to that of IMRT plans with fewer than 50 segments, but was much less than plans created with step and shoot IMRT (ssIMRT) with greater than 50 segments or sliding window techniques [7]. One study has shown that small 2 mm field size (or systematic leaf bank positioning) errors have a measurable impact on the delivered dose and may have consequences for the therapeutic outcome of head and neck cancer patients receiving IMRT [6]. As nasopharynx treatment plans are extremely complex compared to other sites, errors in these plans are hypothesized to have significant dosimetric impacts and be more likely to occur. These systematic uncertainties might arise from equipment malfunctions or miscalibrations [8]. Automatic planned VMAT (ap-VMAT) and automatic IMRT treatment planning has also been shown to improve the quality of head and neck cancer treatment plans and reduce planning time when directly compared to manually planned VMAT (mp-VMAT) plans [9,10]. The best quality plans for both manual and automated VMAT plans are somewhat subjective, with some studies showing that improved VMAT OAR sparing can come at an associated cost of PTV dose inhomogeneity [11]. It has been shown that for head and neck cancers, radiotherapy patients treated in centers with relatively large numbers of cases experienced better survival outcomes than those treated at low volume centers [12]. This may be in part due to better quality radiotherapy, including quality contouring, meeting quality planning objectives and TPS algorithms, quality patient set-up and quality in the entire radiotherapy process. Systematic uncertainties can be minimized through regular quality assurance (QA) procedures. QA practices and their effectiveness vary (due to differing detector systems, software, analysis metrics, protocols and various combinations of these [7,8,13–15]). Similar studies investigating errors have been recently summarised and evaluated for TomoTherapy patients by Deshpande et al. [16].

This work aims to identify the types and magnitudes of errors that are of most impact clinically for nasopharynx radiotherapy patients, and the extent of impact on patient doses to PTVs and OARs. Differences occurring between institutions and/or treatment planning methods (specifically between ap-VMAT, mp-VMAT and mp-ssIMRT) in terms of their robustness to simulated errors are compared.

2. Materials and methods

Ten nasopharynx patients of varying complexity were selected from a previous study from within one institution [17]. These 10 patient datasets, comprising DICOM images and structures, were anonymized and distributed to the participating centers located in Australia and Denmark. VMAT plans were developed within all three institutions according to individual institution protocols. The use of ap-VMAT or mp-VMAT was allowed, and depended on the current clinical practice within each institution. The rationale was to determine if institutions (two with the same vendor linacs and one with a different vendor's linacs) all using the same Treatment Planning System (TPS), but using their own treatment planning VMAT protocols produced similar results. In addition, one institution generated additional plans creating plans with 3 techniques, mp-VMAT, ap-VMAT and mp-ssIMRT. This allowed fair comparison of treatment planning techniques as the planner and dose constraints were from within the same department. Manual planning as defined here for both mp-VMAT and mp-ssIMRT allowed the use of Pinnacle^3 (Philips, Netherlands) hot-scripts already in clinical use within the institution. Treatment planning protocols using mp-VMAT hot-scripts have been described previously [9].

2.1. Multiple institution VMAT

For consistency, the original Clinical Target Volume (CTV), Organ at Risk (OAR) structures and original plan isocenter were utilized by all participating institutions for treatment planning. However, institutions were asked to plan using their own current protocol. The original isocenter provided by institution 1 occasionally differed by only a few millimeters (<2 mm) across institutions where it was adjusted slightly (typically in the superior or inferior direction) to further optimize the plan. Final dose resolution set the dose grid to 0.25 cm × 0.25 cm × 0.25 cm in institution 1 and 0.3 cm × 0.3 cm × 0.3 cm for the others. The three institutions' nasopharynx treatment planning protocols, all planned within Pinnacle^3, are summarized in Table 1.

The uncertainties were simulated by exporting the original baseline Pinnacle^3 plan file and modifying them with an in-house Python code [21,22]. The code introduced systematic shifts of ±1, ±2 and ±5 degrees, to the gantry and collimator angle and the modified plan file was subsequently reimported into Pinnacle^3 to calculate the dose. Identical values, ±1, ±2 and ±5, in millimeters were retained to introduce systematic errors in the Multi-Leaf Collimator Field Size (MLCfs) and Multi-Leaf Collimator Shift (MLCshift).

Table 1
Summary of the three institutions current practice treatment planning approaches.

	Institution 1 mp-VMAT	Institution 2 ap-VMAT	Institution 3 ap-VMAT
Number of Arcs	2	1	2
Gantry angles	(184–176° clockwise and 176–184° anti-clockwise)	180–182° anti-clockwise	(182–178° clockwise and 178–182° anti-clockwise)
Collimator	>5°, <355°	15–30°	0°, 35° or 45°
Couch	0°	0°	0°
Control Point Spacing	4°	2°	4°
Dose levels[a]	PTV1 = 70 Gy PTV2 = 59–63 Gy PTV3 = 54–56 Gy	PTV1 = 68 Gy PTV2 = 60 Gy PTV3 = 50 Gy	PTV1 = 70 Gy PTV2 = 59–63 Gy PTV3 = 54–56 Gy
Prescription for high dose target (PTV1)	70 Gy in 35 fx	68 Gy in 34 fx	70 Gy in 35 fx
Guidelines	ICRU 83 [18] and EviQ [19]	DAHANCA guidelines [20]	ICRU 83 [18] and EviQ [19]
Pinnacle^3 version	9.10	9.10	9.14
Linac vendor	Elekta VersaHD	Elekta VersaHD	Varian Truebeam

[a] Institution 1 and 3, utilized 70, 59–63 and 54–56 Gy target dose ranges for nine patients but only PTV70 and PTV56 Gy for patient 1.