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Assessing the feasibility of volumetric-modulated arc therapy using simultaneous integrated boost (SIB-VMAT): An analysis for complex head-neck, high-risk prostate and rectal cancer cases

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ABSTRACT

Intensity-modulated radiotherapy (IMRT) allowed the simultaneous delivery of different doses to different target volumes within a single fraction, an approach called simultaneous integrated boost (SIB). As consequence, the fraction dose to the boost volume can be increased while keeping low doses to the elective volumes, and the number of fractions and overall treatment time will be reduced, translating into better radiobiological effectiveness. In recent years, volumetric-modulated arc therapy (VMAT) has been shown to provide similar plan quality with respect to fixed-field IMRT but with large reduction in treatment time and monitor units (MUs) number. However, the feasibility of VMAT when used with SIB strategy has few investigations to date. We explored the potential of VMAT in a SIB strategy for complex cancer sites. A total of 15 patients were selected, including 5 head-and-neck, 5 high-risk prostate, and 5 rectal cancer cases. Both a double-arc VMAT and a 7-field IMRT plan were generated for each case using Oncentra MasterPlan treatment planning system for an Elekta Precise linac. Dosimetric indexes for targets and organs at risk (OARs) were compared based on dose-volume histograms. Conformity index, homogeneity index, and dose-contrast index were used for target analyses. The equivalent uniform doses and the normal tissue complication probabilities were calculated for main OARs. MUs number and treatment time were analyzed to score treatment efficiency. Pretreatment dosimetry was performed using 2-dimensional (2D)-array dosimeter. SIB-VMAT plans showed a high level of fluence modulation needed for SIB treatments, high conformal dose distribution, similar target coverage, and a tendency to improve OARs sparing compared with the benchmark SIB-IMRT plans. The median treatment times reduced from 13 to 20 minutes to approximately 5 minutes for all cases with SIB-VMAT, with a MU reduction up to 22.5%. The 2D-array ion-chambers' measurements reported an agreement of more than 95% for a criterion of 3% to 3 mm. SIB-VMAT was able to combine the advantages of conventional SIB-IMRT with its highly conformal dose distribution and OARs sparing and the advantages of 3D-conformal radiotherapy with its fast delivery.

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Introduction

The clinical implementation of intensity-modulated radiotherapy (IMRT) has been associated with a significant reduction of toxicity because of better sparing of critical structures outside the

target volumes.^{1,2} Owing to the high level of dose conformity, tumor-dose escalation can be planned, maintaining the irradiation of critical structures within tolerance. Furthermore, IMRT allowed the simultaneous delivery of different doses to different target volumes within a single fraction, an approach called simultaneous integrated boost (SIB). In 3-dimensional-conformal radiotherapy (3D-CRT), 2 separate plans are needed for the irradiation of 2 different target volumes at different doses. By integrating the boost dose into a single plan simultaneously optimized with inverse planning for all the targets, SIB-IMRT permits to increase

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the fraction dose to the boost volume while keeping the dose to the elective volumes at the same level of conventional treatments. Last, SIB-IMRT involves the use of a single plan for all target volumes, with several organizational benefits in terms of efficiency, with potential reduction of uncertainties related to the sequential treatments. Until now, SIB-IMRT has been introduced in several anatomic sites, providing clinical and dosimetric advantages.^{3–10} However, the high-quality plan attained with SIB-IMRT techniques is achieved at the cost of prolonged delivery time and increased number of monitor units (MUs). Volumetric-modulated arc therapy (VMAT) is a newer technique to deliver modulated dose distributions, in which highly conformal doses can be realized by varying the speed of gantry rotation, multileaf collimator (MLC) shape, and dose rate.¹¹ Several studies have shown that VMAT is able to provide similar plan quality with respect to fixed-field IMRT but with large reduction in treatment time and MUs number in almost all anatomic sites.^{12–21} Plan optimization with SIB strategy requires significant increase in fluence modulation, so as to achieve the desired dose level to primary tumor while minimizing the dose to surrounding tissues. Several articles have shown that fixed-field IMRT can achieve the required level of modulation, but despite the large number of published articles on VMAT, its feasibility and potential advantages when used with a SIB strategy have been investigated mainly for patients with head-and-neck cancer.^{13–15,22–25} On the contrary, few studies focused on the application of VMAT for whole-pelvic nodal irradiation with hypofractionated SIB to prostate or rectal cancer. Some recent studies^{26–28} have successfully analyzed the feasibility of VMAT to provide sufficient modulation for prostate radiotherapy with SIB to a intraprostatic lesion, showing that VMAT allowed dose escalation with better sparing of organs at risk (OARs) than conventional IMRT. High-risk patients with prostate and rectal cancer treated with whole-pelvic nodal radiotherapy (WPRT) represent a higher challenging planning task because of large and irregularly shaped target volumes (as pelvic lymph nodes), which may lead to inadequate target coverage or unacceptable irradiation to OARs or both. Data on the application of VMAT to WPRT are nowadays emerging, with^{29–31} or without^{32–34} the SIB strategy, showing an overall equivalent dosimetric quality as fixed-field IMRT but with a significant improvement in efficiency in treatment delivery. Most of these comparative planning dosimetric studies have been performed almost exclusively for RapidArc technique, and only 1 research group focused on the commercial solution of Oncentra MasterPlan treatment planning system (TPS) with Elekta linacs,^{35,36} but without using the SIB strategy.

The aim of this study was to explore the feasibility and the dosimetric accuracy of SIB-VMAT using the combination Oncentra MasterPlan TPS and Elekta linacs. We evaluated its advantages and shortcomings by comparing the quality of 15 clinical plans of 3 complex anatomic sites in respect to fixed-field IMRT, including head-neck, high-risk prostate and rectal cancer.

Methods and Materials

Patients selection

Three different anatomic sites are presented to demonstrate the potential benefits of SIB-VMAT technique with respect to conventional fixed-field IMRT, which is the clinical practice at our institution since 2004. A total of 15 patients treated with SIB-VMAT were randomly selected, 5 patients for each of the following pathologies: head-neck, high-risk prostate, and rectal cancer. These cases were chosen to represent typical treatments of great clinical complexity routinely performed at our institution. All patients underwent a simulation computed tomography (CT) scan (4-mm slice thickness). Diagnostic imaging (magnetic resonance imaging for rectal and prostate cases and positron emission tomography-CT for head-neck cases) was co-registered with the CT in target volume delineation.

Head-and-neck cancer

A moderately accelerated SIB treatment with concurrent weekly cisplatin after neoadjuvant chemotherapy is our standard treatment plan in patients with advanced head-neck cancer.³⁷ clinical target volume (CTV) 1 was considered as primary tumor and nodes showing metabolic activity at ¹⁸F-fluorodeoxyglucose-positron emission tomography-CT scan. CTV2 was defined as lymph nodes with high-risk of occult metastases. CTV3 included low-risk nodal regions. Anatomic boundaries of lymph nodal regions were outlined according to Grégoire *et al.*³⁸ Corresponding planning target volumes (PTVs) were obtained by adding a 4-mm margin to CTVs. Radiotherapy was prescribed according to SIB technique with all PTVs irradiated simultaneously over 30 daily fractions. Doses of 67.5 Gy (2.25 Gy/fraction), 60.0 Gy (2.0 Gy/fraction), and 55.5 Gy (1.85 Gy/fraction) were prescribed to the PTV1, PTV2, and PTV3, respectively.

Prostate cancer

An accelerated exclusive SIB treatment is routinely performed at our institution in patients with high-risk prostate cancer. CTV1 was delineated as the prostate plus 0.5-cm periprostate tissue and 0.5 to 2.0 cm of caudal seminal vesicles based on risk category³⁹; CTV2 included the obturator, internal and external iliac, and presacral lymph nodes.⁴⁰ PTV2 was obtained by adding an isotropic 8-mm margin to the CTV2; PTV1 was obtained by adding an 8-mm margin in all directions to the CTV1, except posteriorly where a 6-mm margin was given. These margins were based on our protocol, which provides daily image guidance used to localize the prostate by means of intraprostatic fiducial gold markers. The 2 PTVs were simultaneously irradiated over 25 daily fractions at 65.0 Gy (2.6 Gy/fraction) and 45.0 Gy (1.8 Gy/fraction) to the PTV1 and PTV2, respectively. This regimen is similar to the one adopted by Myrehaug *et al.*³⁰

Rectal cancer

Patients with locally advanced rectal cancer are treated with a neoadjuvant accelerated SIB approach. The gross tumor volume was delineated on the basis of magnetic resonance imaging and contrasted-CT imaging. CTV1 included the gross tumor volume and the corresponding rectum and mesorectum plus a 1-cm margin in craniocaudal direction. CTV2 included mesorectum, perirectal and internal iliac nodes, and the areas at risk of local recurrences. In case of extension into the anal canal, the CTV2 included external iliac nodes or inguinal lymph nodes. PTV1 was obtained by adding nonuniform margins to the CTV1 following the suggestions of Nijkamp *et al.*⁴¹ PTV2 was obtained by adding 8-mm uniform margin to the CTV2. The 2 PTVs were simultaneously irradiated over 25 daily fractions with a dose of 57.5 Gy (2.3 Gy/fraction) and 45.0 Gy (1.8 Gy/fraction) to the PTV1 and PTV2, respectively.

Treatment planning

All plans were performed using the Oncentra MasterPlan TPS v.4.1 SP2 (Nucletron BV, Veenendaal, the Netherlands) for 6-MV beams from an Elekta Precise linac (Elekta Ltd., Crawley, UK). Integrated MLC consists of 40 opposed pairs of leaves, with a projected width of 1 cm at the isocenter. No leaf interdigitation is allowed and the minimum gap between the opposed leaves and opposed adjacent leaves is 0.5 cm. The maximal leaf speed is 2.0 cm/s and the total leaf travel distance is 32.5 cm. Jaws cover a full 40 × 40-cm² field.

In all techniques, dose calculation was performed using the pencil-beam algorithm with inhomogeneity correction and a dose-grid resolution of 0.3 × 0.3 cm² in the axial plane (x-z plane). In the direction of y-axis (the slice direction), the resolution of the dose grid was set to be equal to the slice spacing in the CT image series (4 mm). Dose constraints to PTVs and OARs are those commonly used in our clinical routine; doses were converted in their radiobiological equivalent to determine the tolerances listed in Tables 3 and 4. Some nonanatomic dummy volumes were also defined to guide the optimization process to prevent dose dumping in undefined areas.

Benchmark SIB-IMRT plans were optimized with the direct machine optimization approach using 7 coplanar step-and-shoot beams; optimization parameters are shown in Table 3. The maximal number of segments was chosen to range between 15 and 20 per field, depending on the cancer site. The minimum segment area was set to 4 cm², and minimum MU per segment was 3 MUs.

The beam data modeling in Oncentra MasterPlan was implemented with the following nominal values for VMAT specific parameters. The maximal gantry speed is 6° per second, with minimum and maximum MU per degree of gantry rotation equal to 0.1 MU per degree and 20.0 MU per degree, respectively. A continuous variation of dose rate was not allowed for Elekta Precise linac. Five fixed-dose rate levels were selected up to 400 MU/s (the maximum nominal dose rate), each half the dose rate of the next higher level. The fastest combination of dose rate, gantry speed, and leaf speed was automatically selected by the linac control system software Precise Desktop 7 during the arc delivery.

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