Head and neck tomotherapy

A dosimetric comparison of non-coplanar IMRT versus Helical Tomotherapy for nasal cavity and paranasal sinus cancer

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Abstract

**Purposes:** To determine if there are clinically significant differences between the dosimetry of sinus tumors delivered by non-coplanar LINAC-based IMRT techniques and Helical Tomotherapy (HT). HT is capable of delivering highly conformal and uniform target dosimetry. However, HT lacks non-coplanar capability, which is commonly used for linear accelerator-based IMRT for nasal cavity and paranasal sinus tumors.

**Methods and materials:** We selected 10 patients with representative early and advanced nasal cavity and paranasal sinus malignancies treated with a preoperative dose of 50 Gy/25 fractions without coverage of the cervical lymphatics for dosimetric comparison. Each plan was independently optimized using either Corvus inverse treatment planning system, commissioned for a Varian 2300 CD linear accelerator with 1 cm multileaf collimator (MLC) leaves, or the HT inverse treatment planning system. A non-coplanar seven field technique was used in all Corvus plans with five mid-sagittal fields and two anterior oblique fields as described by Claus et al. [F. Claus, W. De Gersem, C. De Wagter, et al., An implementation strategy for IMRT of ethmoid sinus cancer and bilateral sparing of the optic pathways, Int J Radiat Oncol Biol Phys 51 (2001) 318–331], whereas only coplanar beamlets were used in HT planning. Dose plans were compared using DVHs, the minimum PTV dose to 1 cm^3 of the PTV, a uniformity index of planned treatment volume (PTV), and a comprehensive quality index (CQI) based on the maximum dose to optical structures, parotids and the brainstem which were deemed as the most critical adjacent structures.

**Results:** Both planning systems showed comparable PTV dose coverage, but HT had significantly higher uniformity \((p < 0.01)\) inside the PTV. The CQI for all organs at risk were equivalent except ipsilateral lenses and eyes, which received statistically lower dose from HT plans \((p < 0.01)\).

**Conclusions:** Overall HT provided equivalent or slightly better normal structure avoidance with a more uniform PTV dose for nasal cavity and paranasal sinus cancer treatment than non-coplanar LINAC-based IMRT. The disadvantage of coplanar geometry in HT is apparently counterbalanced by the larger number of fields.

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[10–12]. Pacholke et al. found that four field conformal RT was as good as or better than IMRT (non-coplanar IMRT was not included in the comparison) [10]. Tsien et al. also found that IMRT can aid in sparing the optic tracts, however it usually requires some trade-off in dosing to the planned target volume based upon clinical judgment [12].

Helical Tomotherapy (HT) is a novel radiation device capable of delivering a highly conformal dose from a rotational gantry, which allows radiation delivery calculated for approximately every seven degrees of rotation around the patient or 51 fields per rotation [13]. The additional freedom in inverse planning optimization of 51 beam angles usually results in a more uniform target dose, and better avoidance of organs at risk (OARs) compared to standard IMRT using 7–9 coplanar fields (all fields in the same plane) [14]. However, linear accelerator (LINAC)-based IMRT can deliver non-coplanar beams that provide additional inverse planning optimization freedom for OAR avoidance and tumor coverage compared to coplanar LINAC techniques [10,11,15,16]. Non-coplanar beams are delivered by a LINAC by rotating the couch, an option not possible for HT due to the closed gantry design. This limitation could pose a significant geometric problem for certain tumor volumes because adjacent critical structures lie mainly parallel to the target in the axial plane.

In order to compare the dosimetry of HT versus non-coplanar LINAC-based IMRT for nasal cavity and paranasal sinus tumors we planned 10 patients on a Corvus system that is commissioned for a Varian 2300 linear accelerator (LINAC) with 1 cm multi-leaf collimator (MLC) and HT. We compared the respective calculated doses to the planning treatment volumes (PTVs) and doses to the OARs to determine if there was a clinically significant difference between these two techniques.

Methods and materials

Ten patients with representative early and advanced nasal cavity and paranasal sinus malignancies underwent inverse treatment planning using a Corvus™ system and were treated with non-coplanar LINAC-based IMRT on a Varian 2300 LINAC to a preoperative dose of 50 Gy and the planning CT simulation scans were then re-planned on our HT inverse planning system. Patients were simulated in aquaplast masks and a CT simulation was obtained with 3 mm slice thickness. The Gross Target Volume (GTV) was contoured to cover all gross disease and a Clinical Target Volume (CTV) was then contoured to cover microscopic spread of disease at the skull base, surrounding sinuses and adjacent soft tissues for all patients. The CTV was customized based on the anatomic extent of the tumor, but included the ipsilateral mediod orbital wall, the nasal cavity, cribiform plate, bilateral ethmoid sinuses, and the ipsilateral maxillary and frontal osteometal complexes at a minimum with larger expansions depending on tumor location and extent. The CTV was expanded symmetrically by 3 mm in all dimensions to account for patient setup error and motion within the

aquaplast mask to obtain the Planning Treatment Volume (PTV). Normal critical structures included the brainstem, eyes, lens, optic nerves, optic chiasm, and parotid glands. Patient CT images and contours were transferred from the Corvus system to the HT system. The volumes were compared between two planning systems to ensure the accuracy of contour transfer. Plans were optimized to minimize the maximum dose to the optic structures, parotids, and brainstem to as low as possible while covering a minimum of 95% of the PTV with the prescribed dose of 50 Gy. Normal tissue constraints varied on a case by case basis depending on the anatomic location of the PTV and the extent of intracranial and orbital invasion. Six MV photons were used in all plans. For Corvus optimization, five mid-sagittal fields equally spaced by 30° and two anterior oblique fields with gantry angles of 75° and 285° as described by Claus et al. [1] were used. In HT optimization, a field width of 2.5 cm, a pitch of 0.3 and a modulation factor of 2.5 were used for all cases. The volumes of OARs in HT overlapping with the PTV were owned by both the PTV and the OARs but in Corvus they are owned by the OARs. We reassigned the volumes in HT to the OARs only to make the two systems identical in how they handle the dosimetric statistics in overlapping regions. The number of iterations ranged from 100 to 200. A complete block that restricts the optimization algorithm from using beams that enter or exit through the structure was used on all the lenses due to their minimal tolerance of radiation.

In order to assess the uniformity of both plans, a uniformity index was used and defined as:

$$\text{UI} = \frac{D_5}{D_{95}},$$

where $D_5$ and $D_{95}$ are the minimum doses delivered to 5% and 95% of the PTV as previously described by Wang et al. [17]. The greater UI indicates higher heterogeneity. We chose to compare uniformity because of the close proximity of the CTV and the normal structures of the optic pathways, which frequently abut, making it critical that there are no hot spots in the PTV that could expand into these adjacent regions resulting in potential visual loss from optic structure overdosing with slight variations in head positioning. In addition, the minimal dose to 1 cm³ ($D_{\text{min, cm}^3}$) of the PTV was determined for both systems because significant tumor underdosing can potentially lead to local failure.

Because of the individual difference between OARs and PTV and the small volume of optical structures, substantially different absolute doses between patients may affect the statistic. Therefore, normalized quality indices (QI) and a comprehensive quality index (CQI) of surrounding OARs were used and defined as:

$$\text{CQI} = \frac{1}{N} \sum_{i=1}^{N} \text{QI}_i = \frac{1}{N} \sum_{i=1}^{N} \left( \frac{D_{\text{max}}}{D_{\text{max}}^{\text{Corvus}}} \right),$$

In this equation, $i$ is the index of the critical organs, which are (1) ipsilateral eye, (2) contralateral eye, (3) ipsilateral lens, (4) contralateral lens, (5) ipsilateral optical nerve, (6) contralateral optical nerve, (7) optical chiasm and (8) brainstem. CQI was designed to compare the ability of avoiding these eight organs around the PTV given the same
weighting to all organs. Although CQI may overweight certain organs that are below tolerance, we chose this index as it represents a global measure of the capability of avoiding sensitive structures. Individual QIs are shown for direct comparison of each OAR. A CQI less than one indicates that HT provides a better plan for the surrounding OARs, and vice versa. Statistical tests for all comparisons were performed using t-test.

Results

The volume comparison of PTV, eyes, lens, optical nerves and optical chiasms is presented in Table 1. Because of the difference in calculating resolution, a slight difference is observed. However, the difference in volume is generally less than 1% of the volume (for PTV) or less than 0.1 cc (for optical structures).

The proximity of sinus tumors to optic structures resulted in considerable small cold spots in the PTV in both planning systems (Fig. 1). The HT plans had a lower minimum point dose as shown in Fig. 2a, however the mean dose to the 1 cm³ of the PTV that receives the lowest dose is comparable or slightly higher for the HT plans as seen in Fig. 2b.

All 20 plans meet the prescription criteria that 95% of the PTV receives the minimum prescribed dose of 50 Gy. A composite plot is shown in Fig. 3a, where the difference between planning systems is evident: the HT DVH has a steeper slope indicating a higher uniformity within the PTV. The UI for each individual patient is plotted in Fig. 3b. The UIs from HT plans are universally lower than Corvus plans 46.1 ± 1.6 Gy.

The average of the QIs and the standard deviations are also summarized in Table 2. Of all the OARs, the lenses show the most evident improvement with an average dose reduction of 31%, with 90% of lenses receiving a lower maximum dose by HT plans. The mean maximum ipsilateral lens doses for HT and Corvus plans are 9.8 ± 4.2 Gy and 18.6 ± 8.1 Gy; the mean maximum contralateral lens doses for HT and Corvus plans are 7.5 ± 4.0 Gy and 9.3 ± 4.9 Gy, respectively. The improvement of ipsilateral lens dose is statistically significant with p-value <0.01. However, the improvement of contralateral side is not significant. Similar results are observed for eyes, which have significantly (p-value <0.01) improved ipsilateral doses, but not for the contralateral side. For all other organs, the difference is far less than the respective standard deviations and not statistically significant.

Discussion

In a recent study, van Vulpen reported a dosimetric comparison of HT and coplanar LINAC-based IMRT for oropharyngeal carcinoma and concluded that HT provided improved dose homogeneity and reduced dose to certain normal structures [16]. However, these conclusions cannot be extrapolated to nasal cavity and paranasal sinus tumors because these tumors are generally treated with a non-coplanar technique. We therefore investigated the dosimetric differences between non-coplanar IMRT vs. HT to determine if either technique was clinically superior.

In the present study, we found that the non-coplanar LINAC-based plans and HT plans provided adequate PTV coverage, similar PTV \( D_{\text{min,ctm}} \), and roughly equivalent clinically significant OAR avoidance. There are many organs involved in treatment planning of nasal cavity and paranasal sinus tumors that have very small volumes (<2 cm³), such as the lens, optic nerves and chiasm. The accuracy of dose calculation is affected by resolution at this scale. HT offers a dose voxel size of 1.88 × 1.88 × 3 mm versus 4 × 4 × 3 mm for Corvus and the higher spatial resolution of the HT dose computation enables a higher precision for small organ

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Table 1
The volume (cc) comparison between HT and Corvus

<table>
<thead>
<tr>
<th>Patient number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td>PTV</td>
<td>81.82</td>
<td>252.79</td>
<td>658.37</td>
<td>633.01</td>
<td>552.05</td>
<td>223.27</td>
<td>160.88</td>
<td>408.8</td>
<td>555.43</td>
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<td>7.87</td>
<td>7.85</td>
<td>7.8</td>
<td>8.96</td>
<td>8.69</td>
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<td>8.16</td>
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<td>8.16</td>
<td>7.5</td>
<td>9.82</td>
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<td>0.28</td>
<td>0.15</td>
<td>2.14</td>
<td>0.73</td>
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<td>0.09</td>
<td>0.59</td>
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<td>0.12</td>
<td>2.07</td>
<td>NA</td>
<td>0.29</td>
<td>1.17</td>
<td>0.12</td>
<td>1.42</td>
<td>0.21</td>
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<tr>
<td>Optical nerve (ipsilateral)</td>
<td>1.14</td>
<td>0.83</td>
<td>1.08</td>
<td>0.98</td>
<td>1.42</td>
<td>0.97</td>
<td>1.56</td>
<td>1.36</td>
<td>1.55</td>
<td>1.18</td>
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<td>0.92</td>
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<td>1.07</td>
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<td>0.82</td>
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</tr>
<tr>
<td>PTV</td>
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<td>251.2</td>
<td>657.55</td>
<td>633.07</td>
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<td>410.03</td>
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<td>850.64</td>
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<td>7.92</td>
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<td>8.93</td>
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<td>7.15</td>
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<td>9.31</td>
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<tr>
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<td>8.11</td>
<td>7.44</td>
<td>9.84</td>
<td>8.23</td>
<td>7.38</td>
<td>7.98</td>
<td>6.54</td>
<td>9.23</td>
</tr>
<tr>
<td>Lens (ipsilateral)</td>
<td>0.18</td>
<td>0.25</td>
<td>0.14</td>
<td>2.08</td>
<td>0.76</td>
<td>0.21</td>
<td>0.9</td>
<td>0.08</td>
<td>0.6</td>
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<tr>
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<td>0.1</td>
<td>2.13</td>
<td>NA</td>
<td>0.29</td>
<td>1.17</td>
<td>0.12</td>
<td>1.45</td>
<td>0.21</td>
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<tr>
<td>Optical nerve (ipsilateral)</td>
<td>1.21</td>
<td>0.8</td>
<td>1.07</td>
<td>0.91</td>
<td>1.4</td>
<td>0.93</td>
<td>1.55</td>
<td>1.37</td>
<td>1.57</td>
<td>1.27</td>
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<tr>
<td>Optical nerve (contralateral)</td>
<td>0.88</td>
<td>0.86</td>
<td>1.04</td>
<td>1.01</td>
<td>1.46</td>
<td>0.97</td>
<td>1.19</td>
<td>0.57</td>
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<tr>
<td>Optical chiasm</td>
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<td>0.74</td>
<td>0.36</td>
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<td>1.49</td>
<td>1.76</td>
<td>1.78</td>
<td>0.35</td>
<td>1.78</td>
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</table>
dosimetry and subsequently could contribute to the results of our comparison. The dose comparison also relies on the operator. We had two experienced dosimetrists optimizing the plans on each of the planning systems independently. Different operators may weight organ and tumor constraints differently, and since there are more than 10 organs involved in each plan, the comprehensive quality index (CQI) is a more dependable measure of dose to OARs than comparing the individual organs.

Dose uniformity is critical for the treatment of nasal cavity and paranasal sinus tumors since the CTVs of tumors with orbital invasion frequently abut the optic structures and the PTV expansion may include the optic structures. Hot spots in the PTV adjacent to the optic structures could...
put the patient at increased risk of visual loss given the interfraction setup and intrafraction motion uncertainties in treatment delivery. The improved dose homogeneity of HT over the non-coplanar LINAC-based plans could have clinical significance in preventing visual complications. Also, given the rapid dose falloff of plans to treat these tumors while minimizing the dose to adjacent critical structures, any patient setup errors could also result in PTV underdosing. Clearly this would be even more of an issue if definitive doses of 65–70 Gy were prescribed as opposed to preoperative doses of 50 Gy studied here as the dose falloffs would even be steeper for definitive radiotherapy cases. Daily image guidance reduces the risk of patient setup errors with PTV hot spots being delivered into adjacent critical structures or underdosing of the PTV and we plan to use the shift measurements made under daily image guidance after laser setup of marks on aquaplast masks to calculate the dose that would have been delivered with and without image guidance to determine the potential benefit that this adds to the treatment delivery process. The combined time to acquire a megavoltage CT (MVCT) and perform the MVCT/kVCT co-registration and deliver the daily dose on HT is \( \approx 12 – 15 \) min and this compares favorably to the delivery time for non-coplanar LINAC treatments which required on average of 25 min mostly due to the fact that automatic field sequencing was not possible with the non-coplanar fields.

Conclusions

We compared the dosimetry of 10 nasal cavity and paranasal sinus tumor patients planned for non-coplanar LINAC-based IMRT and Helical Tomotherapy (HT) with the PTV prescribed 50 Gy/25 fractions and both planning systems satisfied the PTV prescription requirement but HT delivered a significantly more uniform dose to the PTV and slightly better PTV coverage. The comparison of organs at risk by CQI did not yield a statistically significant difference except the ipsilateral eyes and lenses, for which HT achieved significant lower dose. We conclude that the coplanar geometry of HT resulted in equivalent or slightly superior plans comparing the step-and-shoot standard non-coplanar approach.

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