Dosimetric comparison of single-beam multi-arc and 2-beam multi-arc VMAT optimization in the Monaco treatment planning system

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ABSTRACT

The purpose of this study was to evaluate the dosimetric and practical effects of the Monaco treatment planning system "max arcs-per-beam" optimization parameter in pelvic radiotherapy treatments. We selected for this study a total of 17 previously treated patients with a range of pelvic disease sites including prostate (9), bladder (1), uterus (3), rectum (3), and cervix (1). For each patient, 2 plans were generated, one using an arc-per-beam setting of "1" and another with an arc-per-beam setting of "2" using the volumes and constraints established from the initial clinical treatments. All constraints and dose coverage objects were kept the same between plans, and all plans were normalized to 99.7% to ensure 100% of the planning target volume (PTV) received 95% of the prescription dose. Plans were evaluated for PTV conformity, homogeneity, number of monitor units, number of control points, and overall plan acceptability. Treatment delivery time, patient-specific quality assurance procedures, and the impact on clinical workflow were also assessed. We found that for complex-shaped target volumes (small central volumes with extending arms to cover nodal regions), the use of 2 arc-per-beam (2APB) parameter setting achieved significantly lower average dose-volume histogram values for the rectum $V_{20}$ ($p = 0.0012$) and bladder $V_{30}$ ($p = 0.0036$) while meeting the high dose target constraints. For simple PTV shapes, we found reduced monitor units ($13.47\%, p = 0.0009$) and control points ($8.77\%, p = 0.0004$) using 2APB planning. In addition, we found a beam delivery time reduction of approximately 25%. In summary, the dosimetric benefit, although moderate, was improved over a 1APB setting for complex PTV, and equivalent in other cases. The overall reduced delivery time suggests that the use of multiple arcs per beam could lead to reduced patient-on-table time, increased clinical throughput, and reduced medical physics quality assurance effort.

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Introduction

Volumetric-modulated arc therapy (VMAT) is an intensity-modulated, arc delivery technique that uses inverse planning including degrees of freedom for gantry rotation, aperture shape, and dose rate in radiation optimization and delivery. VMAT has been shown to be effective in reducing delivery time, achieving target coverage, and reducing dose to organs at risk (OARs) over intensity-modulated radiation therapy (IMRT) and 3-dimensional conformal therapy techniques in a variety of clinical studies. In many cases, VMAT performs as well or better dosimetrically than IMRT, but for complex target volumes, like for head and neck cancers, IMRT can be slightly superior to VMAT in terms of OAR sparing. Previous publications have shown that using multiple arcs (as opposed to a single one) results in better target coverage and dose homogeneity but at the cost of a larger low-dose bath, more monitor units (MU), and longer delivery times. Similar studies found that 2-arc plans achieved better dosimetric quality, higher minimum planning target volume (PTV) dose, lower hotspot, and better homogeneity and conformity than single-arc plans or IMRT, again at the cost of delivery efficiency. The general consensus appears to be that the complexity of the target volume determines whether 1 or 2 arcs are necessary. Despite VMAT’s popularity and effectiveness, little has been published regarding clinical or dosimetric impact of using multi-arc, single-beam optimization. That is, a multi-arc single beam is a beam that has at least 2 arc segments, where 1 segment rotates clockwise and the other rotates counterclockwise. One initial study found that by combining together...
several VMAT arcs, a reduction in delivery time up to 33% with no loss of dosimetric plan quality could be achieved.\textsuperscript{10}

Several treatment planning systems (TPSs) offer an option to plan with dual arcs. For instance, in the Pinnacle TPS (Philips Radiation Oncology Systems, Fitchburg, WI), a dual arc refers to 2 arcs that are planned simultaneously but delivered separately (SmartArc). The Monaco (v5.0) TPS (Elekta, Stockholm, Sweden) also provides a multiple arc-per-beam (APB) option, although the implementation is different from Pinnacle, both for the optimization and the delivery. This parameter gives the optimization algorithm the freedom to optimize radiation dose delivery across multiple arcs using a single collimator angle while allowing the gantry to rotate clockwise to a desired angle, then rotate counterclockwise (or vice versa) without stopping radiation delivery.\textsuperscript{11} There is no specific mechanism in the optimization that explicitly accounts for the sequencing parameter difference between 1 and 2 arcs per beam. Thus, it cannot be well understood a priori what dosimetric change results from its use. In this study, we analyze and compare the use of 2 arc-per-beam (2APB) optimized plans with 1 arc-per-beam (1APB) plans for a patient population consisting of pelvic cancers and discuss the resulting potential impact of using single-beam multi-arc optimization on dosimetric plan quality, delivery, quality assurance, and clinical workflow.

Methods

To construct dose matrices for methodological comparison, we performed a retrospective analysis of 17 previously treated patients presenting with various-stage cancer of the prostate (9), bladder (1), uterus (3), rectum (3), and cervix (1), both with (11) and without (6) locoregionally involved lymph nodes. The clinical reference plans were all planned with 1APB for a total of 2 beams. VMAT optimization was performed independently by 2 dosimetrists, each with 3 to 5 years of experience, using current clinical standard of care constraints set by attending physicians. No additional manual optimization adjustments were made to control for variation in dosimetrist ability and experience. Comparative plans using the 2APB setting were generated using coplanar VMAT in the Monaco TPS version 5.0 with Monte Carlo algorithm, a calculation grid of 3.0 mm, and a fixed collimator angle of 30 degrees for 2APB and 30/330 degrees for each respective arc in 1APB plans. Arcs started at gantry of 170 degrees with counterclockwise travel to 190 (−170) and then back to initial 170-degree position. The commissioned Elekta linear accelerator in the Monaco TPS instance was equipped with Agility 160-leaf multileaf collimator in dynamic sliding window mode. In summary, for each patient, a plan was generated containing 2 beams, each beam containing only 1 arc. Another plan was then generated with only 1 beam but with the multiple arc option ("arcs per beam"). Both plans were given the same arc lengths to optimize with. All constraints and dose coverage objects were kept the same between plans, and all plans were normalized to 99.7% to ensure 100% of the PTV received 95% of the prescription dose.

For each plan, we evaluated the PTV conformity index (CI) and homogeneity index, total MU, number of control points (CP), planning time, and beam delivery time. The homogeneity index was defined as $D_{95\%}/D_{5\%}$, where $D_{95\%}$ is the minimum dose in 95% of the PTV, indicating an approximated "maximum dose," and $D_{5\%}$ is the minimum dose in 95% of the PTV, indicating an approximated "minimum dose." The closer the index is to 1, the better the dose homogeneity.\textsuperscript{12} The CI is defined as $V_{PTV}/V_{TV}$ target volume getting reference isodose/target volume; again, with a value closer to 1 indicating a more conformal dose distribution.\textsuperscript{13} Dose distributions were also visually examined by dosimetrists, medical physicists, and attending physicians in the TPS for qualitative comparison. Statistical analysis was performed using $Z$ statistic with a significance level $\alpha = 0.05$ ($p \leq \alpha$), with the null hypothesis that there is no difference between samples.\textsuperscript{14}

Results and Discussion

Dosimetric impact

From the tabulated experimental data, we computed the average percent difference between factors associated with plan quality, shown in Table 1. We found that overall, there was no significant difference in plan homogeneity between the 2 planning methods. However, we did find that the plan MU and CP were higher for 1APB plans than for 2APB plans, and the CI is slightly improved for 1APB plans. Positive difference in conformity for this computation indicates improvement here because all cases had conformity below 1 for both planning techniques. The converse description is true for homogeneity; for example, a positive difference would indicate that 2APB plans were improved over comparable 1APB.

The observed differences largely disappear for complex PTV shape cases when the data are separated by PTV complexity. In this patient population, the PTV shape fell into 2 distinct categories owing to anatomy: (1) complex—small initial PTV with long extending “arms” covering nodal regions (mostly prostate fossa and lymph nodes) and (2) simple—larger, central PTVs (uterus, cervix including parametrial lymph nodes) that are closer to spherical in shape. In Table 2, we see that for simpler shaped PTVs, the higher MU and CP remain for 1APB plans. Given that in this set of patients, the simpler PTVs are also larger (by volume) than the complex PTVs, it naturally follows that more MU and CP are required to deliver the dose than complex plans.

On examination of dose distributions in the TPS, we found several plan instances with evidence of dose reduction to OARs, in particular, more medial structures such as the bladder and rectum. An example of the dose difference is shown in Fig. 1, for 2 different patients with 1APB (top) and 2APB (bottom) plans with complex PTV shapes. Some dose sparing is seen for loops of small bowel (left) and bladder (right), a difference also reflected in dose-volume histograms showing bladder and rectum volumes, seen in Fig. 2.

This observation is borne out in more detail at certain points in the dose-volume histogram. Computing several clinically relevant dose-volume points reveals little difference among the whole patient population studied here. The results of dose-volume point difference for dose to 50% of the rectum ($V_{50\%}^{PTV}$), 50% of the bladder ($V_{50\%}^{Bladder}$), and 40% of the small bowel ($V_{40\%}^{Small bowel}$) are shown in Table 3. However, again splitting these results by PTV complexity and examining lower dose-volume levels of the rectum ($V_{50\%}^{PTV}$), bladder ($V_{50\%}^{Bladder}$), and small bowel ($V_{80\%}^{Small bowel}$) reveals a significant dose reduction, seen in Table 4, for the bladder and rectum doses for complex PTVs when optimizing with 2APB. As mentioned in the Introduction section, to our knowledge there is no explicit algorithm or mechanism in Monaco optimization that handles 2APB plans differently; however, the optimization algorithm may be benefiting from having more degrees of freedom to work with in the segment shape and weight stage of optimization. This is particularly advantageous for complex prostate volumes.

### Table 1
Mean 2APB and 1APB optimized plan parameters

<table>
<thead>
<tr>
<th></th>
<th>2APB</th>
<th>1APB</th>
<th>% difference</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MU</td>
<td>688.2 ± 116.2</td>
<td>744.5 ± 126.6</td>
<td>4.78%</td>
<td>0.0013</td>
</tr>
<tr>
<td>CP</td>
<td>272.2 ± 28.8</td>
<td>284.4 ± 29.9</td>
<td>4.36%</td>
<td>0.882</td>
</tr>
<tr>
<td>HI</td>
<td>1.04 ± 0.01</td>
<td>1.03 ± 0.001</td>
<td>0.92%</td>
<td>0.0023</td>
</tr>
<tr>
<td>CI</td>
<td>0.74 ± 0.23</td>
<td>0.75 ± 0.23</td>
<td>0.61%</td>
<td>0.0384</td>
</tr>
</tbody>
</table>

Values ± standard deviation.

CI, conformity index; CP, control points; HI, homogeneity index; MU, monitor units.

### Table 2
Mean 2APB and 1APB optimized plan parameters grouped by PTV complexity

<table>
<thead>
<tr>
<th></th>
<th>2APB (simple)</th>
<th>1APB (simple)</th>
<th>% difference</th>
<th>$p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>MU</td>
<td>572.9 ± 93.7</td>
<td>654.5 ± 154.1</td>
<td>13.47%</td>
<td>0.0009</td>
</tr>
<tr>
<td>CP</td>
<td>269.2 ± 35.5</td>
<td>291.3 ± 30.0</td>
<td>9.24%</td>
<td>0.0044</td>
</tr>
<tr>
<td>HI</td>
<td>1.04 ± 0.01</td>
<td>1.03 ± 0.01</td>
<td>0.92%</td>
<td>0.0639</td>
</tr>
<tr>
<td>CI</td>
<td>0.82 ± 0.12</td>
<td>0.83 ± 0.13</td>
<td>0.81%</td>
<td>0.3261</td>
</tr>
</tbody>
</table>

Values ± standard deviation.

CI, conformity index; CP, control points; HI, homogeneity index; MU, monitor units.
which include extensive nodal involvement surrounding OARs such as the rectum and the bladder. We found that using 2APB optimization planners could potentially achieve additional sparing, thus reducing risk of complication. Additionally, we did not find a case where 2APB plan was significantly (or even marginally) worse than its 1APB counterpart. This result suggests potential for benefit to head and neck cases where treatment of nodal neck regions is sought while sparing spinal structures, for example, other complex PTVs.

![Fig. 1. Comparison of dose distributions in 2 patients using 2APB (bottom) and 1APB (top) VMAT optimization. Forty-five gray and 20 Gy isodose lines are shown along with shaded PTV volumes.](image)

![Fig. 2. Comparison of dose-volume histograms for 2 patients planned with 2APB (dashed) and 1APB (solid). For some plans, additional organ sparing is achieved by using 2APB (bottom), whereas in others, the difference is negligible (top).](image)
We have presented a comparison of single arc-per-beam and 2 arc-per-beam VMAT optimization planning in the Monaco v5.0 TPS. The results of the comparison showed reduced MUs and CP using 2APB for simple PTV shapes, moderate improvements in OAR sparing for complex target volumes, and considerable reduction in treatment delivery time for both PTV types, which make 2APB planning a more optimal choice for clinical practice. In summary, our results suggest that 2APB planning has dosimetric advantages over 1APB planning for complex PTV volumes often found in lymph node-involved prostate cases, and that for all 2APB plans, a reduction in QA time, QA effort, and clinical delivery time is achieved without loss to dosimetric plan quality.

### References