A dosimetric comparison of 3D DCAT vs. VMAT for palliative and early-stage liver lesions

Authors: Jina Lee, R.T.(T), Caitlyn Huelskamp, R.T.(T), Collin Nappi, R.T.(T), Nishele Lenards, Ph.D., CMD, R.T.(R)(T), FAAMD, Ashley Hunzeker, M.S., CMD, Ashley Cetnar Ph.D., DABR

Medical Dosimetry Program at the University of Wisconsin – La Crosse

Introduction

The liver is a precarious site for various comorbidities and metastatic diseases alike as a major recipient of damage from conditions ranging from obesity, viruses, and excessive alcohol consumption to advanced colorectal cancer. An aggregation of 2020 cancer statistics showed a consistent, yearly increase of primary liver cancer incidence by 2 - 3%, with death rates also following a similar trend. In an effort to treat liver lesions and spare normal tissue, advancements in the radiation oncology field have played a critical role in the selection of volumetric modulated arc therapy (VMAT) over 3D-conventional radiation therapy (3D-CRT). There is an abundance of studies in literature comparing 3D-CRT methods, specifically dynamic arc conformal therapy (DCAT), against VMAT for lung tumors. It would be valuable to explore the potential clinical applicability of DCAT to treat liver tumors with similar techniques.

The differences in the advantages and disadvantages of VMAT and DCAT stems from the fact that the former method uses optimization of multi-leaf collimators (MLCs) while the latter does not. The primary advantage of VMAT is the ability to achieve dose conformity, lower overall toxicity, and better sparing of OAR including non-liver organs and those low dose tolerances such as the lung. However, IMRT methods are also known to produce an increase of low dose, including the volume of the normal liver receiving 15 Gy ($V_{15}$), which is thought to be a dosimetric indicator for predicting radiation induced liver disease (RILD), among other individual factors. Volumetric modulated arc therapy is also associated with increased interplay effect caused by the motion of the liver during breathing cycles and is reported to result in significant intra-fraction variability (> 3.0 mm), with this effect exacerbated by flattening-filter free beams and smaller clinical target volumes (CTV). On the other end of the spectrum, DCAT compensates for the disadvantages of VMAT, but does have clear disadvantages in clinical application of treatments involving irregularly shaped target volumes because intensity modulation is not utilized. Comparisons using VMAT and DCAT for SBRT lung treatments have shown that DCAT had similar conformity and coverage of the tumor, with slightly better avoidance of OAR including volume of the lung receiving 20 Gy ($V_{20}$), tighter 50% isodose...
lines, and a significant reduction of monitor units (MU) with DCAT.\textsuperscript{7} Segment weight optimized (SWO) DCAT produced dosimetrically similar plans to VMAT in favorable conditions where the tumor was not directly adjacent to OAR.\textsuperscript{8} In addition to its technical simplicity, DCAT is more likely to be approved by insurance and therefore provide timely palliative treatment of the liver. However, despite ASTRO guidelines, challenges exist because of lack of accessibility to policies and consensus on coverage to this disease site.\textsuperscript{9,10}

In 2 emerging studies, researchers have observed VMAT versus DCAT for a variety of SBRT liver treatments. Moon et al\textsuperscript{10} showed that the DCAT plan was able to meet planning goals set by the Radiation Therapy Oncology Group (RTOG) SBRT liver protocols, although VMAT was slightly superior in dose distributions to some organs. Researchers also emphasized that, with DCAT, there is less chance of miss because the tumor is in an open field, and there is less concern with quality assurance, calculation, and interplay effect of the MLC leaves.\textsuperscript{10} Although the study by Moon et al\textsuperscript{10} demonstrated the coverage, conformity, and doses to some OAR using VMAT and DCAT for liver lesions varying in size and number, the authors did not investigate the dose to the kidneys, bowels, lung, and $V_{15}$ of the normal liver, which is critical for safe deliverability of a SBRT liver treatment. Thaper et al\textsuperscript{11} also observed reduced MU with DCAT; however, researchers did not find the use of segment shape optimized (SSO) DCAT as advantageous in their clinical evaluation of DCAT vs VMAT for SBRT treatment of the liver, especially for larger planning target volume (PTV) sizes. With recent studies showing the ability of modified 3D-CRT methods such as the use of DCAT to mimic the results of VMAT plans, additional research is required to evaluate the efficacy and applicability of traditional 3D DCAT to the liver under specific conditions. There is an abundance of studies where researchers compared the application of VMAT and DCAT to the lung, with some even suggesting a hybrid of the two to maximize benefits of each method.\textsuperscript{13} However, there is a lack of direct comparisons, consensus, and analysis regarding the 2 methods for SBRT of the liver.

Dynamic arc conformal therapy is used for both early staged and palliative lung tumors due to the physical similarity in size. However, it is possible that the same is true of VMAT for early staged or small metastatic lesions in the liver. It would be beneficial to understand the differences of DCAT and VMAT in the treatment of liver lesions, especially with the increasing demand for optimization and inverse planning which contributes to increasing costs for IMRT as well as cost discrepancies between VMAT and 3D planning.\textsuperscript{14} The problem is that there is a paucity of literature comparing 3D DCAT to VMAT for early-stage or small metastatic liver
lesions. Therefore, the purpose of this study is to determine if the conformity of dose, irradiated volume, and dose to OAR are equivalent or improved with the use of 3D DCAT as an alternative method of treatment when compared to standard VMAT for SBRT treatment of liver lesions. Researchers tested the hypotheses that 3D DCAT for liver lesions will achieve mean doses to (H1A) the heart, (H2A) kidney, (H3A) large bowel, (H4A) small bowel, (H5A) stomach, and (H6A) esophagus, ≤ to those created with VMAT; (H7A) V20 of the lungs will be ≤ to those created by VMAT; (H8A) V15 < 700 cc to the normal liver; (H9A) conformity index (CI) ≥ 1; (H10A) Homogeneity index (HI) ≤ 2; and (H11A) total volume receiving 25 Gy (V25) ≤ to that of VMAT.

Methods and Materials

Patient Selection

Twenty patients with early-stage liver cancer or metastatic liver lesions from a single institution were selected for this study. Patients were between the ages of 45 and 85 years old. The liver lesions were measured between 2.0 and 5.0 cm in the greatest dimension. Patients with lesions smaller or greater than these dimensions were not included in the study. Of the 20 patients selected, 13 had early-stage liver cancer and 7 had metastatic liver lesions.

Patient Setup

Due to the location and type of treatment performed, extensive immobilization was used during CT simulation and throughout treatments to minimize internal organ motion. Use of increased immobilization allowed for treatment margins to be drawn tighter around tumors, helping to reduce potential dose to surrounding critical structures. During CT simulation, a Civco board was attached to the normal simulation table which was used to secure immobilization devices for SBRT. A Q-Fix knee sponge was indexed on the board for patient comfort and to keep the patient’s lower anatomy stable. An arm shuttle was placed superior to the trunk of the patient, with the patient’s head resting on the head rest of the arm shuttle, and their arms bent superiorly to the patient’s head to keep them out of treatment fields. A full body vac-loc bag was placed under the patient’s entire body, from about mid-thigh to their arms. The vac-loc bag was immobilized completely around the patient to refrain the patient from any movement during treatment. Finally, a compression belt was used to apply pressure to the patient’s abdominal region to shrink the range of motion of the abdomen and chest during the breathing cycle, thus reducing internal motion of organs. Breathing cycles were also tracked using 4D motion sensors; however, the plan was contoured, planned, and treated using the average of this cycle.

Contouring
After CT simulation, the datasets were imported into Varian Eclipse Treatment Planning System (TPS) for contouring and fusions with other imaging techniques to aid in delineation the target volumes for the radiation oncologist. Contouring and fusions were done on the average breathing cycle from the 4D scan. Planning objectives, target volumes, and critical structures were partly adopted from RTOG 1112 protocol; therefore, the OAR contoured were the kidneys, small bowel, large bowel, esophagus, stomach, heart, and lungs.\textsuperscript{15}

*Treatment Planning*

Treatment planning for each technique was consistent for all patients. AcurosXB version 13.7 of Varian Eclipse TPS was utilized for the planning aspect of each patient’s conformal and VMAT plans. Treatments were planned for a Varian TrueBeam linear accelerator with 120 HD MLCs. Both VMAT and DCA plans were designed using the energy 10 MV flattening filter free (FFF) for each field. SBRT treatment parameters were used for both techniques. Both VMAT and DCA plans were planned for 50 Gy in 5 fractions. Based on the location of the tumor, beam arrangements for VMAT and DCA techniques slightly differed for each patient to avoid excessive radiation to normal structures. The VMAT plans were designed with 2 - 3 partial arcs approximately 200 - 220º each. Slight collimator rotations were used to maximize MLC blocking based on the tumor volume. The size of the treatment volume also led to variable field sizes between patients. The DCA plans were also designed consistently, with slight variance between patients due to tumor location. The DCA plans were designed to use 3 partial arcs. The order of the partial arcs were a 40º arc, a 5º gap, a 135º arc, another 5º gap, and a 40º arc. The weighting for the 135º arc was weighted 65 - 70 % of the total dose. The weighting for the 40º arcs were equally weighted with the remaining weighting. Collimator rotations and variable field sizes were also used based on the tumor volume and location. Both planning techniques were normalized to 100% of the prescription dose covering 95% of the treatment volume.

*Plan Comparison*

After retrospectively planning VMAT and DCA techniques for each patient, coverage of the treatment volume was compared between the 2 techniques by analyzing the isodose lines and Dose volume histogram (DVH). Since both techniques were normalized to the same value, the isodose lines and dose fall off were considered and compared between the 2 plans. Conformity index, heterogeneity index, and \( V_{25} \) of the treatment volume were both calculated through Eclipse treatment planning software for each plan. Dose metrics were also compared between the VMAT and DCA plans. The comparative dose metrics included: the mean dose of the heart,
kidney, stomach, esophagus, small and large bowel; the V$_{20}$ of the lungs; and the V$_{15}$ of the liver. For each plan using either VMAT or DCAT technique, the dose metrics and dose values were acquired and compared.

**Statistical Analysis**

The raw data for all patients in the study were congregated to find the mean difference and standard deviation resulting from VMAT and DCAT plans. The mean difference was defined as the average difference of either dose, volume, or index values that resulted from VMAT minus DCAT. To test the significance of the mean difference values, a Wilcoxon test and paired t-test were performed by the University of Wisconsin La-Cross Stats Center. The Wilcoxon test was used to calculate the $P$ values for mean doses to the heart, kidney, large bowel, small bowel, and also the V$_{20}$ of the lungs. The paired t-test was used to calculate the $P$ values for mean doses to the esophagus and stomach, V$_{15}$ of the liver, CI, HI, and V$_{25}$ of the treatment volume. A $P$ value < 0.5 indicates that the mean difference value is statistically significant, prompting researchers to reject the null hypothesis. A rejection of the null hypothesis indicates that, based on the data presented in this study, the outcomes from VMAT versus DCAT are statistically significant and different.

**Results**

**Mean Dose to Organs at Risk**

The mean dose difference to the heart, kidneys, large bowel, small bowel, stomach, and esophagus resulting from VMAT minus DCAT were -26.30, -1.01, -32.88, -2.82, -37.5, and -4.81 cGy, respectively. The higher mean dose difference correlated with a larger range for standard deviation. The greatest mean dose differences were to the heart, large bowel, and stomach resulted in $P$ values of 0.0046, 0.0023, and 0.0353, respectively. These $P$-values (< 0.05) indicate the rejection of the null hypothesis, which signifies that there is a difference between the outcome of the plans; the mean dose to the heart (H$_{1A}$), large bowel (H$_{3A}$), and stomach (H$_{5A}$) produced by VMAT is statistically lower than that of DCAT. The $P$-values for the kidneys, small bowel, and esophagus were 0.0696, 0.3223, and 0.792, respectively. These $P$-values (>0.05) indicate that the null hypothesis cannot be rejected; Therefore, the data from this study shows that DCAT is effective in producing a mean dose to the kidneys (H$_{2A}$), small bowel (H$_{4A}$), and esophagus (H$_{6A}$) statistically equivalent to that of VMAT (Table 1).

**Critical Metrics**
To determine the overall safety and efficacy of the plan, the $V_{20}$ of the lungs, $V_{15}$ of the liver, CI, HI, and the $V_{25}$ of the total volume was analyzed. The mean dose difference to the $V_{20}$ of the lungs, $V_{15}$ of the liver, CI, HI, and $V_{25}$ of the total volume resulting from VMAT minus DCAT were $-0.06$, $-61.73$, $-0.18$, $0.06$, and $-46.30$ respectively. The resulting $P$-values for the $V_{15}$ of the liver, CI, HI, and $V_{25}$ of the total volume were $<0.0001$, $<0.0001$, $0.0479$, and $<0.0001$ respectively. These $P$-values ($<0.05$) indicate the rejection of the null hypothesis. Therefore, the $V_{15}$ of the liver ($H_{8A}$), CI ($H_{9A}$), HI ($H_{10A}$) and the $V_{25}$ of the total volume ($H_{11A}$) produced by VMAT is statistically lower than that of DCAT treatment plans. The $P$-value for the $V_{20}$ of the lungs was $0.2622$. This $P$-value ($>0.05$) indicates that the null hypothesis cannot be rejected. Therefore, DCAT is effective in producing a statistically equivalent dose to the $V_{20}$ of the lungs when compared to VMAT (Table 2).
References


Tables

Table 1. Mean difference averaged from all patients’ VMAT and DCAT plans, standard deviation, and P-value for heart, kidneys, large bowel, small bowel, stomach, esophagus, lungs, and liver.

<table>
<thead>
<tr>
<th>OAR</th>
<th>Mean Difference</th>
<th>Standard Deviation</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heart</td>
<td>-26.30</td>
<td>48.24</td>
<td>0.0046</td>
</tr>
<tr>
<td>Kidneys</td>
<td>-1.01</td>
<td>7.50</td>
<td>0.0696</td>
</tr>
<tr>
<td>Large Bowel</td>
<td>-32.88</td>
<td>59.15</td>
<td>0.0023</td>
</tr>
<tr>
<td>Small Bowel</td>
<td>-2.82</td>
<td>17.29</td>
<td>0.3223</td>
</tr>
<tr>
<td>Stomach</td>
<td>-37.5</td>
<td>74.01</td>
<td>0.0353</td>
</tr>
<tr>
<td>Esophagus</td>
<td>-4.81</td>
<td>80.41</td>
<td>0.792</td>
</tr>
</tbody>
</table>

VMAT = Volumetric modulated arc therapy; DCAT = Dynamic conformal arc therapy; OAR = Organs at Risk

Table 2. Mean difference averaged from all patients’ VMAT and DCAT plans, standard deviation, and P-value for CI, HI, and V_{25} of the treatment volume.

<table>
<thead>
<tr>
<th>Critical Metrics</th>
<th>Mean Difference</th>
<th>Standard Deviation</th>
<th>P-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>V_{20} of Lungs</td>
<td>-0.06</td>
<td>0.41</td>
<td>0.2622</td>
</tr>
<tr>
<td>V_{15} of Liver</td>
<td>-61.73</td>
<td>42.66</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>CI</td>
<td>-0.18</td>
<td>0.06</td>
<td>&lt;0.0001</td>
</tr>
<tr>
<td>HI</td>
<td>0.06</td>
<td>0.13</td>
<td>0.0479</td>
</tr>
<tr>
<td>V_{25} of treatment volume</td>
<td>-46.30</td>
<td>31.09</td>
<td>&lt;0.0001</td>
</tr>
</tbody>
</table>

VMAT = Volumetric modulated arc therapy; DCAT = Dynamic conformal arc therapy; V_{20} = volume receiving 20 Gray; V_{15} = volume receiving 15 Gray CI = conformity index; HI = homogeneity index; V_{25} = total volume receiving 25 Gray