Phase-matched Digital Tomosynthesis (DTS) Imaging for Simultaneous Target Verification during Volumetric Modulated Arc Therapy (VMAT) Treatment

Innovation and Impact: Currently, very few target verification techniques are available during VMAT treatment. kV/MV imaging provides 2D anatomical information but not tomographic information. GPS tracking like Calypso (Calypso, Seattle, WA) is also available, but requires invasive procedures and provides no anatomical information. To achieve more accurate and non-invasive target verification simultaneous to VMAT delivery, we developed a new technique--phase-matched DTS to do tomographic imaging of moving targets. It incorporates the respiratory motion of the targets into the reference DTS (Ref-DTS) reconstruction process and provides phase-matched Ref-DTS for comparison with on-board DTS (OBI-DTS). This technique requires less geometric clearance for imaging, less imaging time, less imaging dose, better time-resolution, compared to simultaneous kV-CBCT imaging during VMAT treatment.

Illustration of Phase-Matching:

The technique matches the phases of a planning 4DCT set to those of on-board kV projections acquired during VMAT delivery in order to generate corresponding digitally reconstructed radiography (DRR) for Ref-DTS reconstruction. As illustrated in figure 1: the on-board projections at different angles (indicated by the orange lines) are matched to different phases (indicated by the green bars) of a 4DCT set of the patient to generate a corresponding DRR. DTS images are then reconstructed from both the on-board projections (OBI-DTS) and associated DRRs (phase-matched Ref-DTS) to perform target verification.

The Simulation of 4DCT, AIP, FBCT and On-board Projections: 4D Digital Extended Cardiac Torso Phantom (XCAT) was applied to simulate patient scenarios. A typical breathing pattern (respiratory cycle: 5s, peak-valley amplitude of the diaphragm: 2cm) of a patient was input into the XCAT to simulate the following images:

1. 10-phase simulation 4DCT: dimensions: 512*512*126; pixel size: 0.98 mm; slice thickness: 2.5 mm; 0% and 100% phase corresponding to the end expiration
2. Average intensity projection (AIP): average of the 10 phases of the 4DCT set
3. Free-breathing CT (FBCT): generated by calculating the phase of each slice in the FBCT and then extract them from the corresponding phase of 4DCT and combine them together
4. On-board projections: dimensions: 512*384; pixel size: 0.78 mm; gantry rotating from anterior-posterior (AP) position to left lateral position of the patient; gantry rotation speed: 6 degrees/s; frame rate: 10 frames/s; 0.05 mAs per projection; 140 kVp

DRRs of 4DCT, AIP and FBCT: Dimensions: 512*384; Pixel size: 0.78 mm

Reconstruction and Comparison of the DTS: All DTS sets are reconstructed by Feldkamp–Davis–Kress (FDK) algorithm using 51 projections which cover 30-degree gantry rotation. Images in figure 2 illustrate coronal slices of OBI-DTS and three Ref-DTS sets (Ref-DTS-FBCT, Ref-DTS-AIP, Ref-DTS-4DCT), indicating favorable similarity between Ref-DTS-4DCT and OBI-DTS (Dimensions: 511*320*511; Pixel size: 0.51 mm; Slice thickness: 0.51 mm).
Shifts and Registration: The shifts applied to the simulation CT sets described in the abstract are composed of three groups of different magnitudes: 2 mm, 5 mm and 10 mm. Each group contains 7 shifts in three orthogonal directions and combinations of the directions. For example, for shift magnitude of 2 mm, the shifts contained in the group are (0 0 2), (0 2 0), (2 0 0), (2 2 0), (2 0 2), (0 2 2), (2 2 2). The registration uses a mutual-information based rigid registration method utilizing downhill-simplex algorithm.

1 mm Discrepancy Criterion: The registered shifts have to be within 1 mm discrepancy compared with the simulated shifts in each of the three directions to be viewed successful.

General Flow Chart of the Abstract:

Results: The registration results are shown in Table 1. It can be observed that OBI-DTS/Ref-DTS-4DCT pair provides the best target verification accuracy.

<table>
<thead>
<tr>
<th>Magnitude of Shifts</th>
<th>OBI-DTS/Ref-DTS-AIP</th>
<th>OBI-DTS/Ref-DTS-FBCT</th>
<th>OBI-DTS/Ref-DTS-4DCT</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Success Rate (%)</td>
<td>Total Discrepancy (mm)</td>
<td>Success Rate (%)</td>
</tr>
<tr>
<td>2 mm</td>
<td>28.6%</td>
<td>1.24±0.40</td>
<td>14.3%</td>
</tr>
<tr>
<td>5 mm</td>
<td>14.3%</td>
<td>1.68±0.43</td>
<td>0%</td>
</tr>
<tr>
<td>10 mm</td>
<td>28.6%</td>
<td>1.66±0.36</td>
<td>42.9%</td>
</tr>
</tbody>
</table>

Table 1. Registration Results for Different OBI-DTS/Ref-DTS Pairs. The success rates are based on the 1 mm discrepancy criterion. The ‘total discrepancy’ here is the vector distance discrepancy $\sqrt{\Delta x^2 + \Delta y^2 + \Delta z^2}$. $\Delta x$, $\Delta y$ and $\Delta z$ are the discrepancies in three directions, respectively.

References: