2D/3D registration for real-time intra-fractional tumor motion tracking during radiotherapy

Poster No.: C-2505
Congress: ECR 2012
Type: Scientific Exhibit
Keywords: Radiation therapy / Oncology, Digital radiography, CT, Conventional radiography, Oncology, Lung, Computer applications, Neoplasia, Metastases
DOI: 10.1594/ecr2012/C-2505

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Purpose

Intra-fractional tumor motion is one of the main sources of uncertainty in dose application during radiation therapy. Due to the motion, the planned target volume (PTV) has to be enlarged to ensure complete tumor irradiation which results in an increased dose delivery to healthy tissue. Efforts to compensate for this motion can rely on the implantation of internal or external fiducial markers [1] or on lung motion models [2] for instance. Marker implantation poses an additional burden in clinical routine while on the other hand respiratory models, may suffer from drift problems, an insufficient correlation of organ movement and external markers, and problems in following aperiodic motion.

Our work aims at developing and evaluating a 2D/3D registration framework for markerless real-time tumor tracking during radiation therapy. Tumor tracking, will enable motion compensation with a consequent reduction of the PTV which in turn, has the advantage of protecting healthy tissue from irradiation. The work presented here, extends our previous research where a similar evaluation has been done but where the performance was still well below our goal [3].

We combine the advantage of modern therapy devices, which allow x-ray image acquisition simultaneously to treatment at rates as high as 5.4Hz, with rapid advancements of general purpose graphics processing units (GPGPU) hardware, to implement an on-line registration scheme with a sufficient update rate to allow real-time motion tracking.

Methods and Materials

Our 2D/3D registration method relies solely on intensity-based image processing. X-ray images are acquired during treatment with a frequency of 5.4Hz. Each image is compared with digitally reconstructed radiographs (DRRs), generated from the planning computed tomography (CT). An optimizer will find the spatial transformation generating the most similar DRR to the current x-ray.

The DRRs are generated with a ray-casting algorithm on a NVIDIA Tesla with 960 independent processing cores, programmed using CUDA as described in [4]. The merit function used to measure similarity, is based on normalized mutual information [5]. The registration is done on a region of interest (ROI) corresponding to the PTV, the area where tumor motion occurs and where the assumption of rigid motion is valid.

We evaluated our method off-line using a respiratory phantom and datasets from five clinical patients undergoing therapy. The phantom consists of three spheres connected to a cylinder that can move with one degree of freedom, simulating breathing motion (Fig. 1 on page 3a). The patient datasets consist of the planning volumes (CT) with annotated clinical target volumes (CTVs) and PTVs (Fig. 2 on page 3) and sets of x-rays (between 105 and 150, Fig. 1 on page 3b) acquired during treatment.
For all datasets, we recorded the displacement parameters and the total registration time for each of the x-ray images. The movement of the phantom was simultaneously measured with an optical tracking system. For the patients we compared the measured displacement parameters with the movement of the diaphragm, which was extracted from the x-ray sequences.

Images for this section:

Fig. 1: Example x-ray images acquired from the LINAC. a) phantom and b) patient
Fig. 2: Example patient dataset used for off-line validation of the method. One slice of the 3D dataset, with annotated contours of the lungs, the PTV and the CTV is shown on the left side. On the right, one x-ray with the contours projected is shown.
Results

Fig. 3 on page 5 shows the reconstructed movement along the cranial-caudal (CC), left-right (LR) and anterior-posterior (AP) directions in blue, green and red respectively. The dashed line shows the movement as measured by the optical tracking system. The movement of the phantom along the CC direction was well followed with an rms error of 2.1mm in comparison with the known displacement. The extracted movement along LR and AP directions is very small. The mean registration time was 220ms (4.5Hz).

Fig. 4 on page 6 shows the reconstructed motion along the CC, LR and AP directions for four of the patients. The measured motion along the CC direction clearly correlates with the breathing cycle. Patient four was omitted from the results as the tumor exhibited very little motion due to the fact that it was located in the apex of the lung. The table below shows the rms, amplitude of the displacements and registration times for each of the four patients. The mean registration time is always below 185 ms (5.4Hz). Fig. 5 on page 7 shows a visual example of tumor motion tracking. The figure shows three intra-fractional x-rays, taken at different points in time, where the CTV (in green) is following the results of registration while the PTV (red) is static (see also the movie in Fig. 6 on page 8).

<table>
<thead>
<tr>
<th>RMS</th>
<th>Amplitude</th>
<th>Mean reg. time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC (mm)</td>
<td>LR (mm)</td>
<td>AP (mm)</td>
</tr>
<tr>
<td>Patient 1</td>
<td>2.0</td>
<td>0.9</td>
</tr>
<tr>
<td>Patient 2</td>
<td>1.3</td>
<td>0.8</td>
</tr>
<tr>
<td>Patient 3</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>Patient 5</td>
<td>6.7</td>
<td>N.A.</td>
</tr>
</tbody>
</table>

Rms and maximum amplitude of the tumor motion along CC, LR and AP directions for four of the patients. N.A. (non applicable) is written in the table, when the extracted displacement did not feature a sinusoidal like signal.

Images for this section:
Fig. 3: Reconstructed motion of the phantom displacement along cranial-caudal (blue line), left-right (green line) and anterior-posterior (red line) directions. The dashed line represents the phantom motion measured with an optical tracking system.
Fig. 4: Reconstructed motion of the centroid of the tumor along cranial-caudal (blue line), left-right (green line), anterior-posterior (red line) directions for patients 1, 2, 3 and 5. The diaphragm motion of each patient is shown as a black dotted line.

Fig. 5: Tumor motion tracking example. The images were taken in different points in time. In the images, the planned target volume (PTV), represented in red, is static and
the clinical target volume (CTV) in green, is following the final position extracted by our registration algorithm using the x-rays as input.

**Fig. 6:** Tumor motion tracking video example. The planned target volume (PTV), represented in red, is static and the clinical target volume (CTV) in green, is following the final position extracted by our registration algorithm using the x-rays as input.
Conclusion

The results demonstrate the feasibility of tumor motion tracking with sufficient update rate to process data in real-time. For the phantom, the speed was slightly lower due to the larger ROI. Future improvements, namely the implementation of the merit function calculation in the GPU, will enable real-time processing ever for bigger ROIs.

References


Personal Information

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