Parameter Optimization of a Deformable Lung Model for Real-time Tumor-tracking radiotherapy

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Abstract: Tumor-tracking radiotherapy is recently emerged as an advanced technology for treatment of a lung tumor. In order to achieve accurate irradiation, time-series 3D position of the tumor should be detected from X-ray images. However, image processing algorithms often fail to detect the position of the lung tumor due to low contrast integral images. This study presents a new framework for simulation-based, tumor-tracking radiotherapy. We generate a lung mesh from CT images and estimate the 3D position of the tumor based on a deformable lung model. We propose a framework that optimizes simulation parameters by evaluating similarity between DRR (Digitally Reconstructed Radiograph) of the deformed results and X-ray images measured during the therapy. This presentation reports the details of the methods and experiments with patient data.
Keywords: Lung deformation, Optimization, Digitally Reconstructed Radiograph, Tumor-tracking radiotherapy

1. Introsduction

Radiotherapy is regarded as popular, efficient, less-invasive treatment for cancer. The main challenges in radiotherapy are to preserve as many normal cells as possible while irradiating at the target tumor. In case of a lung cancer, however, lung deformation and the movement of the tumor with respiration make it difficult to irradiate the tumor precisely. The radiation therapy system being developed at the Foundation for Biomedical Research and Innovation (BRI) is capable of swinging the irradiation head according to the gimbals mechanism[1]. If the movement of the lung tumor is accurately predictable or estimated, continuous tumor-tracking irradiation while pursuing the lung tumor can be performed. This approach shortens radiation time as well as avoids radiation of normal cells compared to intercepting radiation approaches [2].

Success in real-time tumor-tracking irradiation requires accurate estimation of the position of the lung tumor during irradiation. Time-series X-ray radiographs can be acquired during treatment. However, image processing of the X-ray radiographs often fail to detect the tumor due to its low contrast integral images. Accordingly, we developed a strategy for radiotherapy planning based on physics-based simulation [3]. A lung mesh is generated from CT images, and the 3D position of the tumor is estimated based on a deformable lung model.

In this presentation, we introduce a framework that optimizes simulation parameters for patients by evaluating similarity between DRR (Digitally Reconstructed Radiograph) generated from the deformed results and X-ray images measured during the therapy. This presentation reports the details of the methods and experiments with patient data.

2. Optimizing Lung Deformation Model

2.1 Lung deformation model

Fig. 1 shows the outline of the proposed framework. Two types of data can be obtained before the treatment begins: CT volume data taken at a respiratory standstill and continuous time series X-ray photographs. The next step is to simulate the lung deformation by FEM using CT volume data. This analysis uses a tetrahedral mesh and treats the lung and the breast as an elastic object (see Fig. 2). The simulation target is lung deformation and movement of tumor caused by respiration.

We categorized vertices $\mathbf{V} = (\mathbf{v}_1, \mathbf{v}_2, ..., \mathbf{v}_n)$ of the mesh into four groups $\mathbf{V}_d$: diaphragm vertices, $\mathbf{V}_t$: trachea vertices, $\mathbf{V}_r$: rib cage vertices and $\mathbf{V}_f$: other free vertices like in Fig 2, and defined boundary conditions on the vertices to solve FEM formulation. The trachea vertices are set to remain in a fixed position, that is, unaffected by the respiratory movement. The vertices on the diaphragm and rib cage are updated based on the sine function (1) and (2) respectively.

$$\Delta \mathbf{v}_i = a_r \sin 2\pi f (t + w_r) \mathbf{n}_i \quad (1)$$

$$\Delta \mathbf{v}_j = a_d \sin 2\pi f (t + w_d) \mathbf{n} j \quad (2)$$

where a_d and a_r are the magnitude of the maximum movement of the rib cage and diaphragm. f is determined by the respiratory cycle of the patient. w_r and w_d represents phase difference between rib cage and diaphragm. Regarding the phase difference $|w_r - w_d|$, $\pi/3$ is used based on the Shirato's work [2]. The movement of rib cage vertices is constrained for one direction as it is small toward the couch. The parameters a_d and a_r are patient specific. Therefore, we focus on optimization of these two parameters in our framework.

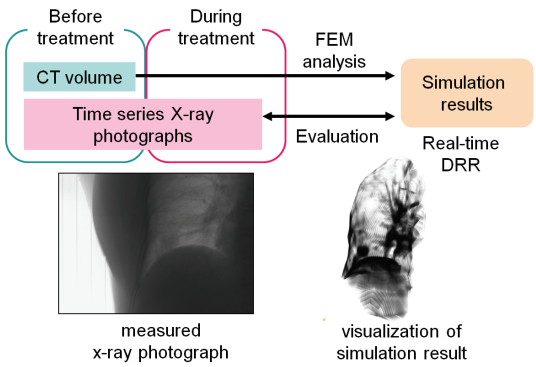

Fig 1. An outline of simulation-based real-time tumor-tracking irradiation. The FE deformation is rendered as DRR and optimized by comparing DRRs with X-ray images.

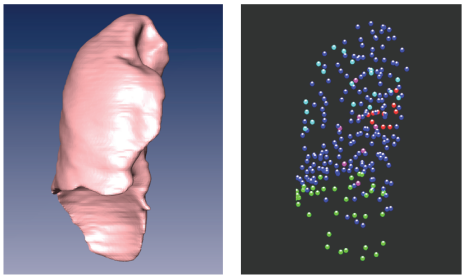

Fig 2. A lung tetrahedral grid constructed from patient CT dataset. (a) polygonal representation and (b) boundary condition

2.2 DRR generation

DRR can be generated by perspective projection of cross sections (proxy geometries) based on texture-based volume rendering algorithm. In our framework, the proxy geometries are defined from tetrahedral mesh [3, 4]. When the vertices of the mesh are displaced by model deformation, the proxy geometries are updated, and the initial grid coordinates are used to map the 3D texture. The voxel values in each tetrahedral element are correctly mapped on the newly created proxy geometries, thereby visualizing the deformed image volumetrically as DRRs.

2.3 Parameter Optimization

DRR and corresponding X-ray image are first registered at an exhalation state by maximizing mutual information of the two images. Deformation of the lung is simulated under the boundary conditions with initialized parameters. In order to optimize the parameters, we evaluate the deformation results by computing similarity between deformed DRR and measured X-ray images. Specifically, mutual information is computed from simulated DRRs with a variety of parameters and the X-ray image at an exhalation state. Finally, we get the optimized parameter that maximizes mutual information.

3. Results

The 3D shape of the lung was obtained from patient CT data through semi-automatic segmentation. A tetrahedral mesh was constructed and its elasticity was set by Young's modulus 0.01 MPa and Poisson's ratio of 0.25. We compute mutual information between deformed DRR and the corresponding X-ray image at an exhalation state. The parameters a_d and a_r are varied from 0mm to 30mm and from 0 mm to 10mm respectively. Then, 10mm and 2mm were obtained as the optimized parameters.

Fig. 3 shows a DRR example of the lung deformation with an optimized parameter. The displacement of the tumor is clearly confirmed on the DRR. In order to validate estimation of the tumor movement, we compared 2D central position of the tumor on the deformed DRR and the X-ray image at a same respiration cycle. The graph in Fig. 4 shows the error of the tumor position between time series X-ray images and simulated DRRs. We confirmed the deformation was successfully simulated with very high accuracy in this clinical case (Error within maximum 1.456 mm, average error 0.65mm)

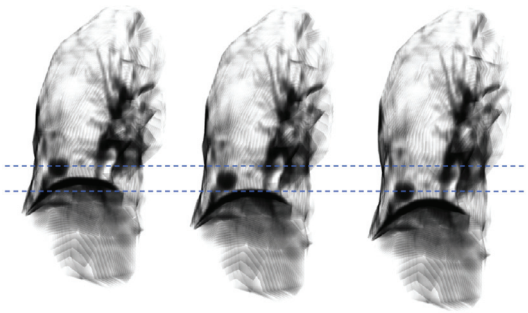

Fig 3. DRR generated from a deformed lung model. The movement of tumor is estimated through the lung deformation model.

4. Conclusion

This paper presented a new respiratory deformation model, and optimization of the deformation parameter for lung tumor location estimation is proposed. The deformation parameter was optimized using patient CT images and X-ray images. We concluded the method is capable of estimating the location of the tumor accurately.

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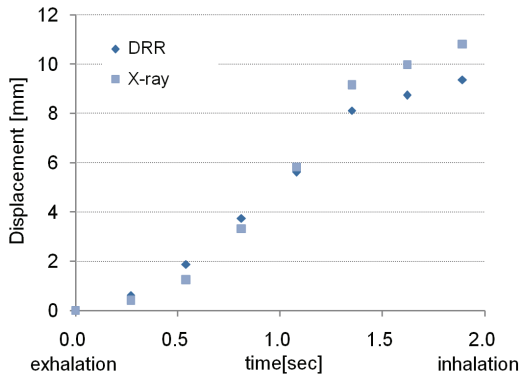

Fig 4. Displacement of the lung tumor in X-ray photographs and in DRRs generated from FE lung simulation results.