Robust 3D lung tumor tracking using maximum likelihood estimation

Introduction Precise knowledge of real-time lung tumor motion during the treatment delivery is essential for the effectiveness of lung cancer radiotherapy. In this work, we develop a method for robust 3D lung tumor tracking using a single x-ray projection without any marker implantation.

Methods and Materials Firstly, 4DCT images at different phases are registered with deformation to yield motion vector fields and a PCA based lung motion model is then built. For an acquired CBCT projection of the same patient, projections of the 4DCT images at all phases are generated at the same projection angle. Comparison between these generated projections and the acquired one yield an estimation of the PCA coefficients, based on the similarity metrics including normalized cross correlation (NCC) and normalized mutual information (NMI) between the gradient images of the acquired CBCT and that of the simulated 4DCT projection, and position of diaphragm. We further fine tune the PCA coefficients in the neighborhood to maximize the similarity metrics. This yields the vector field corresponding to this instantaneous CBCT projection, which can be used to derive the 3D tumor location corresponding to this projection.

Each of the abovementioned three similarity metrics yields an estimated tumor position with some uncertainty. For the sake of robustness, we combine these independent estimations by minimizing the negative logarithm of the maximum likelihood, which is defined as

\[-\ln L = \frac{(x-x_{\text{NCC}})^2}{\sigma_{\text{NCC}}^2} + \frac{(x-x_{\text{NMI}})^2}{\sigma_{\text{NMI}}^2} + \frac{(x-x_{\text{diaphragm}})^2}{\sigma_{\text{diaphragm}}^2} - \frac{(x-\bar{x})^2}{\sigma_{\text{mean}}^2} - \frac{(x-\bar{x})^2}{\sigma_{\text{predict}}^2} \]

Here \(x\) is the tumor position, \(\bar{x}\) the mean value from all the metrics and \(\bar{x}\) the position predicted from the previous positions. Those \(\sigma\)'s are parameters governing to what extent we trust the estimation from the corresponding terms. In practice, \(\sigma_{\text{NCC}}\) and \(\sigma_{\text{NMI}}\) are empirically chosen as the inverse of the similarity metrics, as the higher the metric is, the more reliable it is. The rest of the \(\sigma\)'s are constants that are estimated empirically.

Results NCC, NMI and, diaphragm position all provide some reasonable signals, although none of them can be regarded as accurate at all the gantry angles. After applying the maximum likelihood estimation method, the tumor position can be tracked in a more robust way than any one of the single metrics. The largest of the errors (3.4mm) happens, when the tumor position is beyond its range in the training data. Otherwise the localization error is always below 2mm. The mean error of the results is 1.3mm.

Conclusion We have developed a robust 3D tumor localization method based on the instantaneous CBCT projections using maximum likelihood estimation. Tests conducted in a lung cancer patient have demonstrated the validity of the method.