Motion Modeling of Non-Small Cell Lung Nodules Based on Respiratory Mechanics

Four dimensional imaging techniques are essential in providing spatial and temporal definition of mobile tumors, and furthermore, additional techniques of modeling may cause a decrease in target volumes and increase in therapeutic ratios.

We evaluated the motion of non-small cell lung nodules using auto-registration of 36 4D-CBCT scans for 17 patients. The coordinates of the tumor displacements in relation to the planned tumor location (isocenter) was collected for each ten-phase 4D-CBCT. We constructed a model expecting sinusoidal motion in the x-y-z direction using the equation

\[ f(j) = A_j \sin\left(\frac{2\pi(t - t_0)}{T}\right) + R_0 \]

where \( A_j \) is the maximum displacement, \( t \) is the time of each phase, \( T \) is the period of respiration cycle approximated to four seconds as estimated during scanning, and \( R_0 \) is the average displacement. We fitted \( t_0 \) to account for phase differences as each x-y-z coordinate are not necessarily phase related.

The graph above is the relationship between measured data with measurement error and the modeling curves (dashed lines). The agreement between the model prediction and the measured data was sufficient, with most \( R^2 \) values > 0.9 and within the spatial resolution of the auto-registration and CBCT.

In addition, most patients scanned over the course of treatment have showed spatial and trajectory variations in tumor location and motion trajectories. This may associate with respiration pattern changes among those treatment days for each patient. Real-time respiration tracking may be useful for correction of those variations.
However, most inter-fractional variations fall within the spatial tolerance of the 4D-CBCT data acquisition and auto-registration techniques, as shown in the above figures. These figures show tumor motion trajectories projected on the x-z plane on the left, and dynamic x-y-z displacement versus time for one patient’s target motion variations over four weeks of treatment on the right. Remodeling is suggested as tumor volume and conditions vary significantly over the course of treatment. Notice the largest deviation in amplitude of one direction is ~ 5 mm with an average deviation of 0.6 mm in the x-direction, 0.45 mm in the y-direction, and 0.2 mm in the z-direction.

We also observe specific motion signatures related to specific tumor location, and for these reasons intra-patient modeling is necessary on a case by case basis. Above is comparison of four different patients without phase correction. Even with respiration reduction using abdominal compression, differences of over 5 mm on those patients indicate that the signature tumor motions are patient specific and require individual modeling.

In conclusion, our proposed mechanical modeling of the lung nodule motion seems closely correlated to the actual measured patients’ data. The inter-fractional changes of the modeling parameters for different scans and variations among those patients were studied and require further investigation in order to determine the influential factors for those modeling parameters. Our results are promising for model-based motion predication in treatment of small mobile lung nodules.