AbstractID: 4411 Title: Modeling & Characterization of Respiratory Motion

A quantitative understanding of respiratory motion is critical to improving radiation therapy for lung and upper abdominal cancers. Breathing motion impacts the quality of diagnostic and treatment planning images, causes conformal therapy portals to be larger than the cross-sectional projection of the tumor, and increases irradiated normal organ volumes. Methods intended to reduce or eliminate the impact of breathing motion have been proposed, including breath hold, linear accelerator gating, and tracking either using the linear accelerator or the patient support assembly. A quantitative model of the patient's breathing motion, both tumor and normal organs, is necessary to optimize the gating or tracking methods.

The form of the respiratory model will depend on the ultimate use of the model. In the case of radiation therapy, we are interested in understanding the positions of the tumor and normal organs as a function of time, because our radiation delivery systems operate as a function of time. However, breathing is not sufficiently reproducible to use time directly as the independent model variable. A different, time-dependent metric needs to be selected as the quantity that will be characterized as a function of time and, during acquisition of the motion model data and radiation treatment, be monitored. The metric needs to be: easily measured, quantitative, reproducible, and correlated with breathing motion. Metrics that have been proposed include abdomen or thorax height, abdomen circumference, and spirometry-measured tidal volume.

The motion model requires input data to provide the patient-specific parameters. The input data is typically derived from CT scans that are acquired while the patient undergoes simultaneous monitoring of the metric. This process is labeled "4D CT" in that multiple CT scans are acquired at each location, each scan acquired at a different time. CT scans are typically reconstructed or resorted at a variety of breathing phases. The reconstructed CT scans are then used to determine tumor and normal organ positions as a function of the breathing metric.

In the use of respiratory motion modeling there are some confusing and overlapping uses for the word "phase" that are worth differentiating. Firstly, the use of the term "breathing phase" is used to describe a general part of the breathing cycle, such as mid-inhalation. Secondly, "phase angle" is used to describe a hypothetical angle used when the breathing cycle is described as a periodic function of time, and finally, "phase" itself is used for any quantitatively defined breathing state.

Prior to the development of a biophysically based breathing motion model, there have been two competing methods for describing the behavior of the metric as a function of time; phase-angle and amplitude. Phase-angle descriptions divide the breathing cycles between selected breathing phases, for example, inhalation. The time between successive inhalations is recast linearly as an angle from 0 to 2π (alternatively, some investigators separate the inhalation and exhalation processes, placing 0 and π at inhalation and exhalation, respectively, with linear time interpolation between these breathing phases). In the phase-angle approach, each inhalation and exhalation is treated equally, irrespective of the depth of breathing, but the model can accurately characterize variations in breathing frequency (at least retrospectively). In this model, the description of motion as a function of phase angle can either be the positions as a function of angle or be written as periodic functions with parameters that provide the positions. The phase-based process is capable of describing the hysteresis-like motion of lung tumors well, but is not capable of adequately describing variations in breathing depth. Patient breathing training is often employed to reduce variations in breathing depth.

Amplitude-based methods describe the tumor and organ positions as a function of the metric's amplitude, or numerical value. The time-dependence of the breathing cycle is taken from the time-dependence of the metric amplitude. The amplitude-based approaches are capable of describing variations in breathing depth, but because modeling of hysteresis requires degeneracy in tumor positions as a function of amplitude, hysteresis is not easily described using the amplitude models.

While both amplitude and phase-based models have been utilized to define and describe breathing motion, neither can adequately model even the simplest breathing motion, namely the amplitude-variable hysteresis motion of lung tumors and normal organs that is known to exist. Recently a breathing model has been proposed that describes tissue positions as a function of tidal volume, namely the amount of air inhaled and exhaled during the breathing process. The model assumes that lung tissue positions vary as a function of tidal volume, or in other words, the deeper the breath, the farther the tissues move in their trajectories. Hysteresis is hypothesized to be due to pressure imbalances within the lung tissues that create the variations in trajectory between inhalation and exhalation. The pressure imbalances are assumed to be linearly proportional to the airflow (time derivative of the tidal volume). The position of a piece of lung tissue is therefore a function of its location at a reference breathing phase (e.g. tidal exhalation), the tidal volume and airflow relative to the reference breathing phase. Incidentally, while tidal volume has been used as the metric, any metric that is proportional to tidal volume and its temporal derivative can be used as the metric. For example, published reports indicate that abdomen height is linearly related to tidal volume for quiet respiration.

Understanding the variables that govern respiratory motion is insufficient to describe the positions; a mathematical model is still required. The simplest, namely a linear relationship between position and tidal volume and position and airflow, where the two position components are treated as independent, has been used and appears to provide good descriptions of breathing motion, although supporting data is still limited.

The process of modeling breathing motion is still in its beginning stages, but there are promising approaches being studied. Assuming that the models can accurately describe breathing motion, they will be key components in the treatment planning process.