Introduction

The goal of radiation therapy is to ensure precise and accurate delivery of a curative radiation dose to a tumour while limiting the exposure of surrounding healthy tissues and critical structures to radiation and so avoid serious treatment complications. Radiation therapy for localized cancers of the lung is common and often applied in daily fractions over a few weeks. Intra-fraction tumour motion is often induced by the patient’s respiration and it is this motion that poses a major challenge for precise radiation treatment delivery, especially when the amplitude of tumour motion is greater than a centimeter. Understanding and characterizing the natural tumour motion behavior in various locations is of some importance to precision radiation treatment delivery. Once understood and characterized, prediction of this tumour motion behavior will facilitate advanced real-time treatment of patients under free breathing conditions.

It is known that tumours of the lung, kidney, liver or prostate have distinctive respiratory-induced motion properties. The objective of this work is to identify the correlation between respiratory-induced tumour motion characteristics and its location in the lungs. Establishing reliable correlations between the motion characteristics and tumour location will enable refinement of the predictive...
power of recently developed models for respiratory-induced tumour motion, such as the recently developed finite state model56.

Materials and methods

Materials

A retrospective study was performed on lung tumour motion data for patients previously treated using the real-time tumour-tracking (RTRT) system available at Hokkaido University7. In this RTRT system, a 2mm or 1.5mm diameter gold marker is inserted into or near the lung tumour using image guided implantation. The system can detect the actual marker position at a rate of 30Hz using two X-ray imaging systems. Lung tumour motion data of 42 patients treated between 2001 and 2002 were analyzed.

Introduction to the finite state model

Our previous research introduced a finite state model based on the understanding of natural breathing actions5. In this model, a normal breathing cycle is decomposed into three states: inhale (IN), exhale (EX), and end of exhale (EOE), Figure 1a. A fourth state is also introduced to handle irregular breathing (IRR). IRR state includes any abnormal tumour motion, such as the motion when a patient coughed. Each state is represented by a single line segment. The transition from one state to another is automatically guided by a finite state model (FSM). The example provided in Figure 1 is for one-dimensional motion in the superior-inferior direction. This real-time algorithm has been applied successfully in the analysis of tumour motion for 42 lung cancer patients. This model is the base of the mathematical characterization of tumour motion patterns in our study.

Statistical analysis

Tumour motion analysis based on the FSM allows grouping of patients with similar tumour motion characteristics into subsets and facilitates better modeling and predictive accuracy of the tumour’s motion in real time67. Statistical analysis was performed on each of the defined motion characteristics. Some of these characteristics illustrated in Figure 1d, including state travel distance (such as l0 for EX state), cycle travel distance (such as l0 + l1 + l2), state duration (such as δ0 for EX state), and cycle duration (such as δ0 + δ1 + δ2). The aggregates (including the minimum, maximum, average, range and standard deviation) and histogram of these properties were quantified12.

Correlating tumour motion with location in the lungs

Tumours were clustered based on the associations between their motion characteristics and their location. Figure 2a is a schematic of the location of 36 tumours selected from the database of 42 patients. (In the database, the positions of some tumours were not recorded.) The regions of the lung described in Figure 2 follow the prescription provided by the web site “Get Body Smart by ConceptCreators, Inc”8. Patient’s left and right lungs are each categorized into 10 regions (S1 through S10). Indicated in the figure is an annotation describing whether the tumour was free or attached to another structure, and if it was located in the anterior or posterior half of the lung. The regions S1 through S10 correspond to recognized broncho-pulmonary segments which have been previously used to describe tumour location911.

Translation of the available data on patient tumour location and adhesion status was required since the original patient data defined geometrical information based on; the primary site of the tumour, the broncho-pulmonary segment, the cranio-caudal location (upper, middle or lower), the ventro-dorsal location (anterior, middle or posterior), tumour adhesion to the heart, aorta, chest wall or
The correlation of average cycle travel distance with tumour location in the lungs. (a) Tumour locations based on broncho-pulmonary segments, where Attached means a tumour is attached to one or more of: the chest wall, the vertebra, the aorta or aortic arch and Free means the tumour does not attach to any of these structures. (b) Tumour locations whose cycle travel distance is less than 10mm; (c) tumour locations whose cycle travel distance is between 10mm and 20mm, and (d) tumour locations whose cycle travel distance is more than 20mm.

if it was free of attachment. Other information included the distance from the heart or chest wall.

Results

The duration and travel distance of a breathing state or a breathing cycle was computed for each of the tumours (the comprehensive results are summarized in Wu et al, 2007). The histograms of the average state and cycle travel distance and duration are illustrated in Figure 3a-b. It can be seen that tumour motion characteristics are highly patient specific.

The correlations between tumour motion characteristics and tumour locations are analyzed. Figure 3c provides an example of the correlation between cycle travel distance and lung segments. Based on the significance of the cycle travel distance, four patient clusters were identified. Then, tumours in each of these clusters were mapped back onto the lung anatomy as shown in Figures 2b-d, where Figure 2b is for the locations of tumours in cluster C1, Figure 2c is for C2 and Figure 2d is for the combination of C3 and C4.

Discussion and conclusions

Figures 2 and 3 illustrate the correlations between tumour location and cycle travel distance. For superior-inferior motion, tumours with less motion (cycle travel distance<10mm) are either in left lung segment S1+2 and right S1 or are attached to fixed structures. Tumours with medium motion (10mm<cycle travel distance<20mm) are typically free and centrally located (S3 or S4) or close to the diaphragm (S7, S8 or S10). Tumours with large motion (cycle travel distance>20mm) are free and close to the lung periphery including the diaphragm.

Similar analysis has been performed for IN, EX and EOE travel distances and duration. The results of the IN and EX travel distance correlation with tumour locations are similar to the overall cycle travel distance. The EOE travel distance had no strong correlation with tumour location (The EOE state has little travel distance in comparison to the IN and EX states.). Further analysis showed that there is not a strong correlation between the tumour motion duration parameters and the tumour location.

Knowledge of the tumour travel distance correlation with lung location that is described in this article will help to refine predictive models of tumour motion behavior critical to real-time treatment. Future work will concentrate on correlating the inter- and intra-fractional changes of tumour characteristics with tumour locations.
Reference


JTIENT-SPECIFIC MARGINS FOR PROTON THERAPY OF LUNG

Li Zhao1, G A Sandison 2, J. B. Farr2, Wen-Chien Hsi3, Huanmei Wu4 and X. Allen Li5

1School of Health Sciences, Purdue University, West Lafayette, IN, USA
2Midwest Proton Radiotherapy Institute, Bloomington, IN, USA
3University of Florida Proton Therapy Institute, Jacksonville, FL, USA
4Indiana University Purdue University Indianapolis, Indianapolis, IN, USA
5Department of Radiation Oncology, Medical College of Wisconsin, Milwaukee, WI, USA

Sandison@purdue.edu

Abstract

Lung cancer treatment presents a greater treatment planning and treatment delivery challenge in proton beam therapy compared to conventional photon therapy due to the proton beam’s energy deposition sensitivity to the breathing-induced dynamic tissue density variations along the beam path. Four-dimensional computed tomography (4D-CT) has been defined as the explicit inclusion of temporal changes of tumor and normal organ mobility into an image series. It allows more accurate delineation of lung cancer target volumes by suppression of any breathing motion artifacts present in the CT images. It also allows analysis of the tumor’s 3D spatial movement within a breathing phase cycle. The motivation for this study was to investigate dosimetric errors caused by lung tumor motion in order to find an optimal method of design for patient compensators and apertures for a passive scattering beam delivery system and treatment of the patient under free breathing conditions. In this study, the maximum intensity projection (MIP) method was compared to patient-specific internal margin designs based on a single breathing phase at the end-of-inhale (EOI) or middle-of-exhale (MOE). It was found that MIP method provides superior tumor dose distribution compared to patient-specific internal margin designs derived from 4D-CT.

Keywords 4D-CT, proton therapy, lung tumor, maximum intensity projection

Introduction

Proton beam radiation therapy offers some distinct advantages compared to photon therapy since the proton beam’s enhanced dose deposition region known as the Bragg peak may be exploited for the irradiation of a tumor and the rapid fall-off in dose just beyond the Bragg Peak may provide increased sparing of normal tissue from damage. A few studies have reported a possible benefit of proton therapy in the treatment of lung cancer 1-3. However the proton beam’s range is well-defined by the composite electron density of tissue along its path and compared to photon treatment this makes proton beam treatment more sensitive to lung motion during breathing and the dynamic change in lung density.

The conventional method to address organ motion and setup errors is to expand the treatment volumes. Using ICRU 624 nomenclature, an internal margin (IM) is added for the variation in position and/or shape and size of the clinical target volume (CTV), as seen during simulations, to define the internal target volume (ITV). Geometric misses of the target may occur if the tumor motion is greater than expected on the basis of the simulator or there may be some unnecessary irradiation of the surrounding normal tissue if the tumor motion is smaller than expected.

In common clinical technique, fluoroscopy is acquired during simulation to aid in estimation of the internal margin. Free-breathing CT or breath-hold CT scans are