Quantitative Measurement and Modeling of Target Volume Changes by Respiratory Motion in CT and Cone-Beam CT

Introduction: The location, length and volume of tumors are affected by respiratory motion in cancer patients treated with radiotherapy. Usually these effects are described qualitatively as image blurring in CT and CBCT. In this study, these effects were investigated quantitatively by measuring volume changes for different motion amplitude and frequency using CT and cone-beam CT (CBCT) imaging. A model that predicts the target volume dependence on motion amplitude, frequency, size of the GTV, speed of CT and CBCT scanning was developed.

Method and Materials: Three targets of differing sizes (small: 10x50x30 mm$^3$, medium: 20x50x30 mm$^3$, and large: 40x50x30 mm$^3$) were constructed of tissue-equivalent gel bolus material and embedded into artificial lung within a heterogeneous solid water phantom. Respiratory motion was mimicked by a mobile phantom at a respiration frequency of 15 cycles per minute for eight different amplitudes of respiratory motion in the range 0-20 mm. Images obtained for free-breathing CT and CBCT were contoured and the target volumes and superior-inferior lengths were calculated. Following image data collection, a novel mathematical model and computer simulation were developed to quantify and reproduce observed variations in target volumes and lengths due to motion artifacts.

Results: The measured volumes and lengths of the different targets increased by blurring artifacts of respiratory motion in CBCT images because of blurring image artifacts from long scanning times (about 1 minute) as shown in Fig. 1a. The volumes and lengths were enlarged linearly with the respiratory motion amplitude of the mobile phantom (Fig. 1a). However, in CT images, the target volumes and lengths could increase or decrease by being imaged while the CT scanning is parallel or opposed to the direction of the moving phantom (Fig. 1b). The volume or length enlargement or shrinkage depended on several parameters such as motion amplitude, frequency, size of the target volume, speed of CT scanning. A model was developed that describes the target and length volume variation and its dependence on the previous parameters as shown in Fig. 1c. For each target size and ROM, simulation defined upper and lower bounds for all possible variations in target volumes imaged with CT (Fig. 1c).

Conclusion: The measurement and modeling of target volume and length variations provided precise quantitative assessment of induced artifacts in CBCT and CT imaging by respiratory motion. The modeling of imaging artifacts induced by respiratory motion in CT and CBCT can be used to define accurately gross tumor volumes and organs-at-risk which will be very useful for accurate treatment planning and dose delivery.

Figure 1:
(a) Length variation of the target volume as a function of motion amplitude for a fixed frequency of 15 Hz using full-fan CBCT. The linear curve represents model prediction of length. (b) Length variation as a function of motion amplitude for a fixed frequency of 15 Hz using CT imaging. (c) Range of possible lengths of a 10 mm target obtained from simulation and modeling of volume/length variation for a phantom moving with motion amplitudes in the range from 0-40 mm at fixed 15 Hz imaged with CT.