## Real-time simulation framework for lung tumor radiation therapy

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Lung tumors move during breathing depending on patient's breathing conditions, thereby compromising the accurate deposition of radiation doses. It is thus important to calculate the delivered dose to various aspects of the moving tumor and the surrounding normal tissues due to change in tumor shape and location with breathing. In this abstract, we present a computer-based simulation framework that models a volumetric lung tumor, simulates the tumor motion during radiation therapy, and predicts the amount and location of radiation doses deposited in the moving lung tumor during the actual delivery of radiation. It will also provide insights on the variations in the effectiveness of the therapy for changes in the patient's breathing conditions. The simulation framework concists of a virtual cuboid of dimension 100X100X100 cubes created with each cube of the dimension 1X1X1 cubic mm. The 3D model (spherical, for validation purposes) of the tumor is introduced inside the cuboid. For every breathing step, the centroid of the lung tumor is translated in a randomly selected trajectory. Each 3D vertex inside the moving tumor is traced within the cuboid using binary level-set searching algorithm. To simulate radiation dose delivered, a radiation treatment plan of a small lung tumor was developed in a commercial planning system (BrainScan software, BrainLab). The dose for each radiation field was extracted as a 10cm cube to match the above described simulation cuboid. During the simulation of lung tumor motion, the dose on the target was summed to generate real-time dose to the target for each beam independently. The simulation results are validated by film dosimetry measurements using a physical lung phantom with a moving spherical tumor.

## Introduction

The focus of the current work is for enhancing radiation therapy for lung tumors. Lung tumors move unpredictably depending on patient breathing patterns, thereby changing tumor location that subsequently compromises the accurate deposition of radiation doses. This study involved developing a real-time simulation method to calculate the delivered dose to various aspects of the moving tumor. Such real-time simulations of the actual location and shape of the tumor during the delivery of radiation would enable the use of high focused radiation fields that could result in decreased treatment related toxicitiy. The simulation framework takes into account the patient specific lung tumor motion extracted from Computed Tomography images and the radiation plan prescribed for the patient. The output of the simulation framework would predict the amount and location of radiation doses deposited in both moving lung tumors and surrounding normal lung tissues during the actual delivery of radiation. It will also provide insights on the variations in the effectiveness of the therapy for changes in the patient's breathing conditions.

## Background

The goal in radiation therapy is to deliver a high dose to a tumor while sparing normal tissue. Most dose calculations and evaluations of a planned course of treatment are performed on images of the patient taken prior to treatment. These images are usually high quality CT scans so that the physician, physicists and dosimetrists can identify normal structures to be spared from radiation and the tumor and other involved tissue that must be targeted. Dose calculations on CT scans can use many different models. Traditionally, dose calculations were performed using tabulated data and when multiple treatment fields were used, they would be added to represent a composite dose. With the advent of CT scans to represent patient anatomy, the ability to accurately represent the physics of the radiation beam became possible and the dose calculations have evolved to use a convolution pencil beam algorithms [1] and Monte-Carlo dose calculations [2].

While these dosimetry methods are accurate in representing the physics of the radiation interactions, there remains a major concern that the CT images that are used for these calculations do not adequately represent the patient anatomy at the time of radiation treatment. Due to variations in the patient position from day to day (setup uncertainties), as well as internal changes from day to day (inter-fraction motion), and internal changes during a single radiation treatment (intrafraction), it is customary to use a larger target volume than what is visualized on the CT images to ensure adequate coverage of the target.[3] This is particularly a concern when high radiation doses are delivered with the intent of ablating tumors, in an environment that includes radiation sensitive structures such as normal lung tissue, esophagus and nerve tissue to name a few. In recent studies, 4D CT scans or multiple CT scans at different days have been used to assess the range of target motion and to more adequately define the margins for motion.[4] Once the target motion has been described, a dose model may be able to be combined with the probability distribution of the target motion with the fluence pencil beams from the treatment machine to calculate dose.[5-7] These calculations, although accurate for the CT scan they are calculated on, are still not developed in real-time.

To date, delivery of radiation therapy has been done without any assessment of the dosimetric accuracy of the delivered doses at the time of the actual delivery of radiation. Many assumptions about the integrity of the delivered dose are typically made prior and after the radiation delivery. This would be similar to a surgeon performing a surgery today on the basis of many assumptions made about the patient's anatomy documented on a CT from days ago, in addition to not knowing during the procedure itself exactly where the knife went and how much (i.e. how completely) the tumor was damaged. The proposed technique utilizes a novel combination of techniques used for the first time in clinical radiotherapy. This proposed method calculate delivered dose in real-time to a model representing tumor motion and lung deformation. Because this model is developed for 3D simulation of the lung structure and tumor without the need for CT images during the radiation delivery per se, a dose model will be developed based on pre-calculated doses.

## Materials and methods

Studies have been done at our institution to evaluate optimal lung treatment planning for highly conformal and high dose fractionations. We have developed an in-house protocol for stereotactic body radiotherapy of lung tumors that will delivery the entire treatment in a single session. As part of the preliminary work for this protocol, multiple treatment plans were developed to ensure that conformal beams could be aimed at the tumor that would provide adequate sparing of the normal tissues. In this planning exercise the BrainScan™ software from BrainLab was used since this is the clinical system used to treat lung patients. A

sample dose distribution is shown below with the small lung tumor receiving very high doses and the normal tissues receiving less dose. Plans were generated on ten patients who had undergone radiation therapy. In all cases the tumor was planned to receive a dose of 40 Gy minimum to the edge of the target on a single CT scan with no margin. For this purpose, it was assumed that target motion would be eliminated due to beam delivery options allowing gating of radiation beam. In all cases the target coverage was adequate and all normal tissues and organs at risk were below the acceptable levels of approximately 20% of prescribed dose.

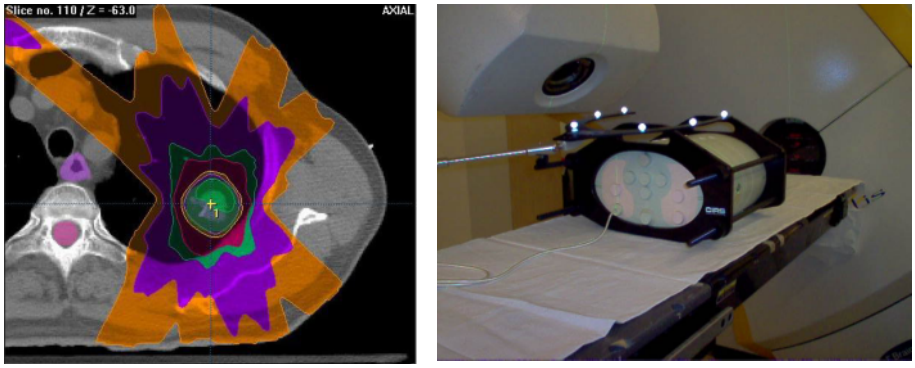


Fig. 1. (a) Dose distribution for a small lung tumor planned to receive 40 Gy in 1 fraction. (b) Phantom for dose validation.

Verifications of the treatment delivery method were tested by using a phantom with ion chamber measurements as shown in Fig. 1. The measurements at the center of the target agreed with planned results within 5% in all cases and within 3% in 80% of the cases. This illustrates that it is possible to verify the dose model of the treatment planning system within approximately 3% of calculated dose. As the lung deformation and tumor motion model is under development, dosimetric calculations and the affects of target motion on dose have been evaluated using film dosimetry and phantom work. This work includes studies of the clinically used gating system in use at our institution which shows that tumor motion can have a significant affect of the edges of a single beam. As the dose calculation model that is being proposed would use structures and not CT information in order to calculate dose, several simplifications have been made in the initial work to extract and calculate dose to a moving object.

## Results

The simulation framework concists of a virtual cuboid of dimension 100X100X100 cubes created with each cube of the dimension 1X1X1 cubic mm. A 3D sphere representing the lung tumor is then introduced in the virtual cuboid. The sphere was then modeled to move in the direction perpendicular to the radiation fields in a similar manner to patient motion. For one study, a modeled tumor of 2.0 cm was developed to move +- 2.0 cm. A dose distribution plan was developed for a tumor of 1.8 mm (for illustration purposes this was designed smaller than the target to illustrate undercoverage and bleeding of dose due to motion). For most lung treatments, between 6 and 9 conformal beams are aimed at the target. For this illustration, 7 equally spaced coplanar beams were targeted at slightly irregularly shaped 1.8 cm target. The dose from each beam was extracted independently to represent a cube (in the virtual cuboid) of dose from each field. In addition the dose rates from each beam were calculated so that the time estimated model can accurately be passed through the dose cube to accumulate dose to the target. This process is repeated for each radiation beam while the spherical target is moved in the cubic phantom. The collision of the beam with the moving spheroid is computed using level-set searching algorithm. Fig. 2a represents the dose that was deposited to the sphere without the introduction of motion, and Fig. 2b represents the dose that was accumulated to the sphere as the target was moved. This simple approach to dose calculations is similar to the early evolution of dose calculations and although simplified in its approach is the first time that real-time dosimetry calculations have been explored to illustrate dose deposited while being delivered.

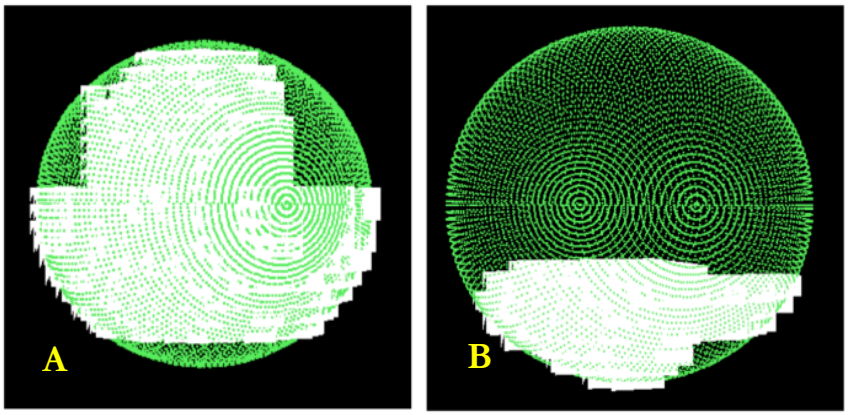


Fig. 2. Dose model for spherical tumor motion (A) and with motion (B).

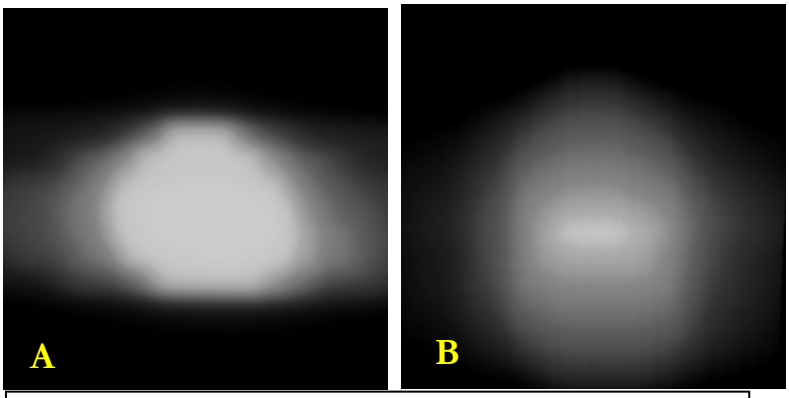


Fig. 3. Dose delivery (films) without motion (A) and with motion (B).

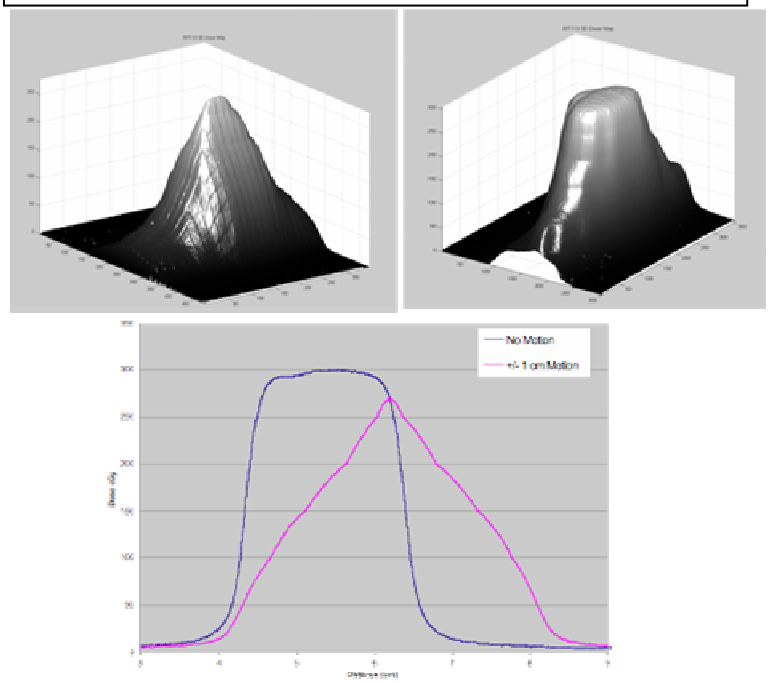


Fig. 4. Comparison of doses documented by film dosimetry with (a) tumor motion and (b) without tumor motion. The center line of the files in both the above cases are plotted in (c).

To validate the dose that is calculated by this addition technique, film was placed into a phantom that could move in the same way as the model. For this purpose, motion was only introduced in one dimension for simplification, however, all motion is possible in the model. Fig 3a-b represent the grey scale images of the films with no motion (Fig 3a) and with motion (Fig 3b). Fig 4a-b represents the 3D plot of the film delivered to match the simulation above shows a 3D display of the sagittal film that was moved in the same manner as the simulation above. This distribution shown on the left is without any motion introduced and the image on the right is with motion matching the motion simulated in the sphere represented above. A comparison between the motion and no motion in plane plots taken from a sagittal film are shown below in Fig. 4c. The no motion film was taken in a position representing expiration breath hold. This explains the overlap region on the motion plot near the inferior portion of the film.

## Conclusion

A method for simulating and visualizing the lung tumor motion and its dosimetry is described. This would allow oncologists to have the ability to visually see radiation doses depositing during the process of radiation therapy delivery, and appreciate discrepancies in actual delivery. Future work would include correlating clinical outcomes to dosimetric information. Once fully developed, this could potentially lead to real time therapeutic approaches that would include adjustments of treatment inaccuracies. Normal tissue tolerance would potentially be better since there is now the ability to document, modify and limit unnecessary irradiation of normal tissues. Although the current paper describes a process that is specific to radiation therapy, the real-time simulation technology could be applied to other non-invasive treatment techniques (such as cryotherapy, radiofrequency ablation or high intensity ultrasound). Apart from lung cancers, this technique could clearly be applied to different anatomic sites, with the ability to tailor the output to idiosyncracies of these different anatomic sites.

## References


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