AbstractID: 9660 Title: Pre-clinical evaluation of a 4D tracking DmMLC-based delivery to lung tumor

**Purpose**
The aim of this study is to provide a pre-clinical evaluation of four-dimensional tracking radiation therapy to lung tumor using a prototype tracking system. The evaluation was based on films dosimetric analysis, time delay measurements and treatment planning DVH analysis by using two types of dynamic phantoms.

**Materials**
The key component of the 4DTRT system was a prototype of TrackBeam. It consists of an image processing tools and a first-of-its-kind dual-layer micro MLC. DmMLC has two layers of orthogonal leaves which provide advantages in speed and conformality when forming beam aperture for tracking. The TrackBeam was mounted to a Varian Linac and connected to a workstation which process the online MV fluence and controls each leaf’s motion. A Quasar dynamic phantom was used for radiographic film irradiation with 4DTRT and also 3DCRT. The phantom has a Gafchromic film insert and a gold marker in the insert. It can move in Sinusoid mode as well as real patient respiratory cycle. Another tissue-equivalent thorax dynamic phantom was used for DVH analysis after a phantom-based 3DCRT planning and a 4DTRT planning developed respectively.

**Results**
The synchronization of marker motion and the DmMLC leaf motion was achieved within less than 0.05 seconds. The films analysis indicated that total 29.91% over the tolerance of 5% and 5.09% of over the tolerance of 5% when the 3DCRT and 4DTRT films compared to a static film. The DVH comparisons indicate 4DTRT reduces significant dose to the Ring from 75% (80% volume) to 60% (50% volume). 4DTRT also reduces considerable amount dose to the total lung from 33% (30% volume) to 22% (22%).

**Conclusion**
The 4D tracking using MLC provides a feasible solution delivering conformal dose to lung tumor and spare the surrounding tissue.

**Conflict of interest**
The work was partially supported by Initia-RT medical device.
I: Propose

Lung tumors are susceptible to motion due to respiration. The aim of this project is to develop and evaluate an innovative method to track and account for tumor motion in the lung during radiation therapy treatment. The concept for four-dimensional tracking radiation therapy (4DTRT) can be shortly explained as to control the beam following the target motion. As the beam aperture is formed by using dynamic MLC, the challenging part for 4DTRT is how to move the MLC leaves to form a tracking beam according to the motion of target.

Here we performed a pre-clinical evaluation using a 4DTRT prototype device, TrackBeam (Cannon, MA) and various dynamic phantoms. The evaluation was based on films dosimetric analysis, time delay measurements and treatment planning DVH analysis.

II: Method and Materials

The 4D tracking radiation therapy architecture of the TrackBeam can be illustrated as Figure 1(a). The x-rays that are used to treat the patient can also be used to take a radiographic image of the patient. Imaging using high energy x-rays has lower contrast and anatomical resolution as compared to low energy x-rays. However, the image resolution can be very accurately visualized if fiducial gold markers were implanted in patient. As the marker’s motion is detected from the imaging detector, the shape and orientation of the radiation beam will change to follow (track) the tumor motion.

Figure 1(b) shows the 4DTRT evaluation settings in our clinic using the prototype of TrackBeam. It consists two major parts, the devices and the image processing tools (IPT). The devices include a megavoltage (MV) X-ray beam, a moving target with marker, a MV image detector, and a first-of-its-kind dual-layer MLC, with its beam eye view shown in Figure 1(c). Dual-layer micro MLC (DmMLC) gives advantages in forming beam aperture conformal and fast by offering two sets of orthogonal leaves.1

The main diagram consists of four steps as following to illustrate how to move the MLC leaves to form a tracking beam according to the motion of target.

Step A collects the MV fluence by the MV image detector. The fluence is obtained through a moving target with an implanted marker inside. The marker creates a contrast area which is identified as the marker position projected to the image detector, as shown in Figure 1(e).

Step B transfers the collected MV fluence image to IPT. The image processing tools play an indispensable role in the integrated system. It converts the MV image which indicates the moving marker position to the MLC leaf controller. IPT is a set of C++ classes and ActiveX controls including low and high-level image processing and analysis functions.

Step C provides the connection between the IPT and MLC leaf controller. After the MV image is processed, a MLC leaf controller file is generated and delivered to the MLC Leaf Controller.

Step D provides the tracking beam which is generated by re-positioning the MLC leaves according to the target motion.

Figure 1: 4D Tracking RT architecture and evaluation settings in Clinic, (a) Concept of 4DTRT, (b) 4DTRT evaluation settings with TrackBeam mounted on a Varian Linac, (c) A typical beam eye view of the Dual-layer MLC, (d) Gafchromic EBT film insert with a marker inside for the dynamic phantom, (e) MV fluence collection by the Image Detector with a circular aperture.

In the 4DTRT, the adaptive function was developed based on the advanced Kalman filter. Since the time delay, experienced between the DmMLC positioning and the moving markers, is one of the major factors that can cause errors in any target tracking system we have implemented the adaptive function, which reduces the positioning lag.

The Quasar respiratory dynamic phantom is used in the evaluation with Gafchromic films in the film insert. The whole tracking system was mounted to a Varian 600C. The X-ray beam goes through the DmMLC and the respiratory phantom. The MV Image Detector collects the MV fluence. The Gafchromic films collect the irradiation dose during 4DTRT.
The DmMLC consists of the upper layer (Y-axis travel) and the lower layer (X-axis travel) of leaves, as shown in Figure 1(c). The upper and lower layers of MLC leaves are perpendicular to the central axis and travel orthogonally to each other. Each leaf is controlled by individual motors, traveling at maximum speeds of 20 mm/sec.

III: Results

A. Marker Trajectory measurements

In the 4DTRT system, all tracked leaves were re-positioned during the real-time tracking based on the moving marker. A 2 mm diameter golden seed, which can be imaged by the MV image detector of the 4DTRT system, was placed in the phantom to indicate the tumor position. The marker trajectory was processed through the IPT. The motion scale in the Quasar respiratory phantom displayed the exact distance for the moving target as it traveled from the end-inhale phase to the end-exhale phase. The trajectory of marker was projected to the Image Detector, processed by IPT and recorded for each individual position. The entire individual trajectory was accumulated in a plot which was capable of showing the marker trajectory during the 4D tracking delivery. A circle of 4 cm in diameter was generated as the aperture shape. Figure 2(a) shows the integrated marker trajectory when the respiratory phantom moves from the end-inhale phase to end-exhale phase at a distance of 20 mm and at a respiratory rate of 5 sec/cycle. The integrated mark trajectory is accumulated in a straight line which is the projection of marker motion. The grid size in Figure 2(a) is 1 mm. The vertical distance from the trajectory bottom to the top is exactly 20 grid units which match well with the marker motion distance as 20 mm. The horizontal vibration of the trajectory was within the 1.0 mm range. The Figure 2(a) demonstrated the MV Image Detector of the tracking system is capable of accurately detecting the marker trajectory.

B. Time delay between the marker and the MLC leaf

The time delay between the marker motion and MLC leaf motion was evaluated during the tracking. In the beginning, the MLC leaf followed the motion of the marker. Therefore, it is unavoidable to have a time lag between the marker and the MLC in the first 1~2 respiratory cycles. The IPT provided an adaptive function to calculate the time delay between the marker and MLC leaves and offered an adaptive function to minimize the time lag. The real-time tracking system has a maximum 0.1 to 0.2 seconds time delay between the DmMLC motion and the target motion during the first 1 ~ 2 cycles (motion elongation 20 mm, 5 sec/cycle). The synchronization of marker motion and the DmMLC leaf motion was achieved within less than 0.05 seconds averaged over the sampled points of measurements. The time delay measurements were carried on the trajectory as shown in Figure 2(b) and DmMLC leaf position accordingly as shown in Figure 3. The DmMLC leaves synchronized to the marker position dynamically.

Figure 2: (a) Marker trajectory projected in the Image Detector, mesh grid as 1.0 mm, (b) Phantom Sinusoid motion cycle with 8 measurement points marked out

Figure 3: DmMLC leaves motion corresponding to the marker motion in one respiratory cycle
C. Film Dosimetric Analysis

In order to evaluate the effect of real-time tumor tracking, we performed dosimetric comparisons for three evaluation patterns, named as the Static, three-dimensional conformal RT (3DCRT), and the 4DTRT pattern.

The Static pattern was based on the assumption that the moving tumor is in still status during treatment. For lung tumors, a realistic scenario during radiotherapy is that the tumor is in motion. So it comes with two additional evaluated patterns in which the tumor is in motion.

The 3DCRT pattern has been widely used in clinic. Figure 4(b-1) shows a schematic layout of clinical radiotherapy for moving tumor. Assuming a target moves +/- 10 mm in superior/inferior (SI) direction. The purple contour, the planned tumor volume (PTV), gives an additional 10 mm margin to overcome the motion of tumor. The red field shape was delivered dose to the moving target and its surrounding tissue.

The 4DTRT pattern was based on the real-time tracking radiation therapy in which the MLC generates the moving beam by relocating the leaves position following the tumor motion.

In these three patterns, the dose delivery to the tumor was 250 cGy. DmMLC was set to generate a circle aperture radiation field with 4 cm in diameter when the beam was perpendicular to the phantom film insert. The tumor motion was simulated in a 5.0 sec/cycle sinusoid moving pattern with amplitude of +/- 10 mm in the superior-inferior (SI) direction.

Figure 4 shows the Gafchromic films of the Static, 3DCRT and 4DTRT pattern respectively. In the Clinical pattern, the irradiation field was blurred due to tumor motion and resulted in a distortion shape along the moving direction (SI direction). On the other hand, the irradiation field with real-time tumor tracking was rounded with much less blur as compared to the Clinical pattern.

For further analyzing the dose characteristics of the moving patterns against the static pattern, the planar dose subtraction was used to compare the difference in dose distributions of two images. The difference plot is based on pixel-by-pixel subtraction of two co-registered images. This type of plot is capable of not only showing the amplitude of the dose difference between two images, but also of displaying the areas where the images difference exists.
Figure 5(a) indicates the dosimetric comparison of the 3DCRT pattern against the Static pattern, which is selected the reference pattern. The 3DCRT pattern offers a conformal dose delivery to the tumor with less than 5% dose difference compared to the Static pattern inside the static tumor. However, there is an unavoidable over-delivery of dose to the surrounding tissue. 29.91% of the total pixel exceeds the selected tolerance of 5% with the maximum difference ranging up to 69%.

Figure 5(b) indicates the dosimetric comparison of the 4DTRT pattern against the Static pattern. The 4DTRT pattern delivers conformal dose to the tumor as well with less than 5% dose difference compared to the Static pattern inside the static tumor. Meanwhile, there is much less over-delivered/under-delivered dose to the surrounding tissue than that of the 3DCRT-Static comparison. In the 4DTRT-Static comparison, only 5.09% of the total pixels exceed the selected tolerance of 5% with the maximum difference ranging up to 35%.

D. Dose volume histogram (DVH) analysis for a treatment planning based on the CIRS Dynamic Phantom

The 4DTRT provides the feasibility of reducing the additional margin which clinically used to overcome the tumor motion. A CIRS tissue-equivalent dynamic thorax phantom was used for tracking purpose and for treatment planning analysis. We tested the CIRS dynamic phantom in the tracking system with same evaluation setting above and it performed as well the Quasar regarding to its capability of tracking. We scanned the phantom and developed a treatment planning to the phantom using Anterior/posterior (AP) and PA two beams. The green ring was obtained by expanding the planned target volume (PTV) by 3 cm, which was used to represent the tumor surrounding tissue. In the 3DCRT planning a 2.0 cm margin to PTV was used and a 0.5 cm margin to PTV in 4DTRT, with isodose lines shown in Figure 6(a) and 6(b) respectively.

Figure 6(c) the solid lines representing the 3DCRT plan and the dashed lines representing 4DTRT. The DVH comparisons indicate 4DTRT plan gives conformal coverage to PTV, with 95% of the volume covered by 94% of the dose. The 4DTRT plan reduces significant dose to the Ring from 75% (80% volume) to 60% (50% volume). The 4DTRT plan also reduces considerable amount dose to the total lung from 33% (30% volume) to 22% (22%).

IV: Conclusion

We evaluated a 4D tracking delivery and provided dosimetric analysis based on radiographic films and DVH analysis of a 3DCRT and 4DTRT planning based on dynamic phantoms. Lung tumors are susceptible to motion due to respiration. The objective of dose delivery is to provide full coverage to tumor as possible and meanwhile limit the dose to the normal tissue as possible. A 4D tracking delivery to the moving tumor provides a feasible solution to that objective based on the pre-clinical evaluation as most of the work on 4DRT can be regarded as a proof-of-principle and 4DRT is still in its early stage of development2.

Reference

1. Liu YX, Shi CY, Tynan P, Papanikolaou N. Dual layer MLC dosimetric characteristics for small field and IMRT applications, Journal of Applied Clinical Medical Physics. (Accepted, Dec 2007)