Title

Technical note: Real-time image-guided adaptive radiotherapy of a rigid target for a prototype fixed beam radiotherapy system

Authors

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Abstract

Purpose

Fixed beam radiotherapy systems utilize couch movement and rotation instead of gantry rotation in order to simplify linear accelerator design. We investigate the ability to deliver fixed beam treatments with the same level of clinical accuracy as conventional (rotating beam) treatments using real-time image guidance to maintain this accuracy in the presence of rigid target motion.

Methods

A prototype fixed beam radiotherapy system was built using a standard linac with the beam fixed in the vertical position and a computer controlled rotation stage that rotated a rigid phantom about the superior-inferior axis. Kilovoltage Intrafraction Monitoring (KIM) and real-time beam adaptation with MLC tracking was applied to a 5-field IMRT treatment

plan with motion introduced to the phantom. The same IMRT treatment was also delivered with real-time adaptation using the conventional rotating beam geometry. Film dosimetry was used to measure the dose delivered with a fixed beam compared to a rotating beam, as well as to compare treatments delivered with and without real-time adaptation.

Results

The dose distributions were found to be equivalent between the fixed beam and rotating beam geometry for real-time adaptive radiotherapy using KIM and MLC tracking beam adaptation. Gamma analysis on the films showed agreement >98% using a 2%/2mm criteria with adaptation for static shifts and periodic motion.

Conclusions

Fixed beam treatments with real-time beam adaptation are dosimetrically equivalent to conventional treatments with a rotating beam, even in the presence of rigid target motion. This suggests that, for a rigid target, the high clinical accuracy of real-time adaptive radiotherapy can be achieved with simpler beam geometry.

1. INTRODUCTION

Radiotherapy is a fundamental part of cancer treatment and is recommended for half of all patients with cancer[1]. However, it is estimated that there are currently just 13,956 radiotherapy machines worldwide and an estimated 21,800 additional machines will needed by 2030 to meet demand[2]. The global shortfall in radiotherapy has been caused in part by the large capital requirements, operation costs, complexity in implementation and staffing required to set up and maintain a radiotherapy facility[3].

One approach to improving global access to radiotherapy is the development of smaller and simpler treatment systems, such as those with a fixed radiation beam[4]. A fixed radiation beam negates the costs and the engineering challenges of rotating the heavy components of the gantry with high accuracy and results in a machine with fewer moving parts to break down. Rotation of the target should allow the same beam geometries and dose distributions to be achieved. The smaller footprint and lower shielding requirements relative to rotating gantry linacs can provide further economic benefits by allowing linacs to be installed in smaller bunkers or in existing Co-60 bunkers[5].

Real-time image guidance and beam adaptation are emerging as crucial components of a patient-centered and automated treatment paradigm. Kilovoltage Intrafraction Monitoring (KIM) and MLC tracking are technologies that monitor and compensate for target motion. KIM is a real-time target localization method that utilizes the gantry-mounted on-board kV imager (OBI) to track the 3D position of implanted fiducial markers[6,7]. KIM has been used to monitor over 1,200 fractions for prostate cancer across five cancer centers[8]. MLC tracking is a beam adaptation method that recalculates MLC leaf positions in real-time based on target location[9]. MLC tracking has been used to treat over 800 fractions for prostate and lung

cancer[10]. Both techniques have been clinically implemented using a Varian Trilogy linac, providing real-time image-guided adaptive radiotherapy to account for rigid motion [11].

The purpose of this study is to demonstrate the feasibility of a fixed beam treatment system with real-time image guidance and beam adaptation. Our first aim is to show equivalence between the dose distributions from a rotating beam treatment (where the treatment beam rotates about a static target) and a fixed beam treatment (where the target rotates under a static, vertical treatment beam). Our second aim is to validate KIM and MLC tracking algorithms for a fixed beam treatment and show that these techniques can account for target motion under rotation in all three spatial dimensions.

2. METHODS AND MATERIALS

A prototype fixed beam radiotherapy system was built with two components: a standard Varian Trilogy linac (Varian Medical Systems, Palo Alto, USA) and a rotating platform. The linac was kept stationary at 0° to simulate a fixed vertical beam. KIM and MLC tracking algorithms were used with the linac's onboard kV imaging system to enable real-time image guidance and beam adaptation. To demonstrate the fixed beam concept, an IMRT plan was delivered using this prototype system, both with and without target motion. The dose distribution delivered using the fixed beam method was measured and compared to that delivered using the conventional rotating gantry method.

2.A. Phantom Rotation

An acrylic phantom containing 3 embedded fiducial markers surrounding a 2.15 cm^3 epoxy tumour analogue was securely mounted on a rotating platform (described throughout as the phantom rotation platform). The phantom rotation platform (Figure 1) is a custom-designed,

computer controlled device designed to rotate about the superior-inferior axis that acts as a miniature prototype of a patient rotation system. The phantom rotation platform was placed under the Trilogy linear accelerator such that its axis of rotation was aligned with the axis of rotation of the gantry, i.e. the treatment isocenter. The centroid of the three markers represents the centre of mass of the tumour target and was also aligned with the treatment plan isocenter.

The alignment of the axis of rotation to the gantry isocenter was confirmed prior to irradiation. At discrete angles, images of the phantom were taken with the on-board imager (OBI) by rotating the gantry and then repeated by rotating the phantom. The average difference between the marker positions in images taken by rotating the gantry and in corresponding images taken by rotating the phantom across all angles was measured to be 0.38 ± 0.11 mm, with a maximum difference of 0.63 ± 0.10 mm. The misalignment between the patient rotation platform and the gantry isocenter results in a small offset measured to be 0.34 ± 0.31 mm, with maximum of 0.77 mm.

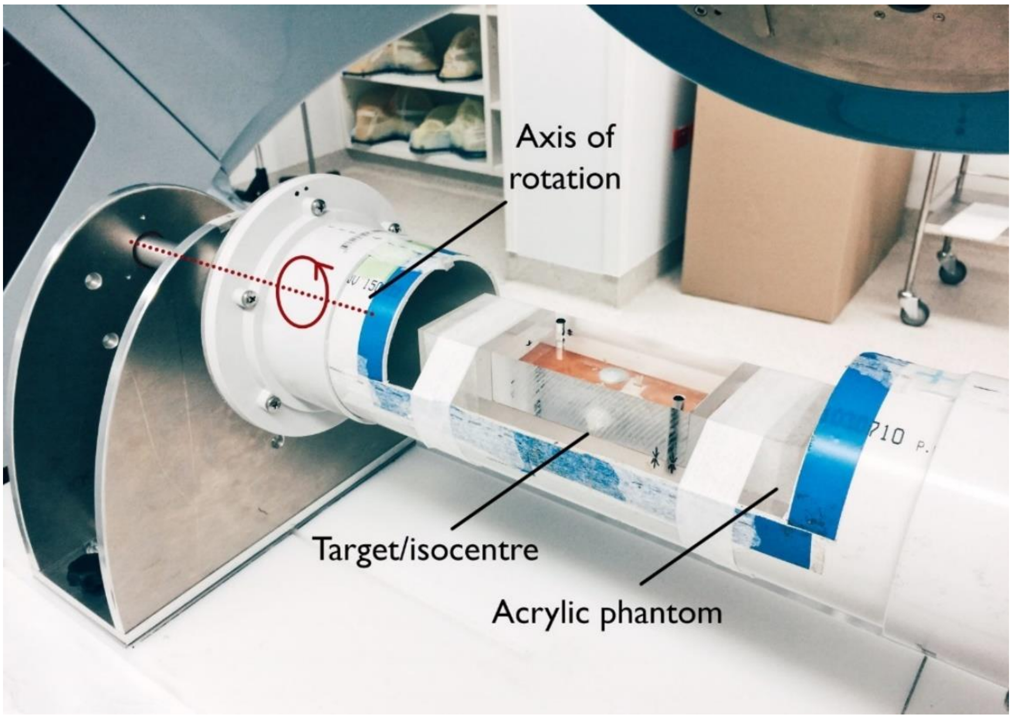

Fig 1. Setup of the acrylic phantom and the phantom rotation platform where the marker centroid, isocenter and axis of rotation are aligned.

2.B. Treatment Delivery

A 6 MV x-ray IMRT plan was created to deliver 6 Gy to a CTV delineated around the tumour target. The plan consisted of 5 fields with gantry angles of 0°, 60°, 110°, 250°, 310° (the rotating beam treatment) and a dose rate of 600 MU min^{-1}. A modified version of this plan (the fixed beam treatment) was created with the same treatment fields but with a fixed gantry angle of 0°. Both the rotating beam treatment and the fixed beam treatment were delivered on the same linac with the same radiation beam and with the phantom and rotation platform set-up in the same position. While the rotating beam treatment was delivered conventionally, the fixed beam treatment was delivered by rotating the phantom between treatment fields to the desired angle (Figure 2B). To investigate the dosimetric equivalence between the rotating beam and fixed beam treatments, both treatment plans were delivered to the phantom aligned at the radiation isocenter.

2.C. Kilovoltage Intrafraction Monitoring and MLC Tracking

Real-time image guidance was applied for both static and dynamic movements of the phantom during a fixed beam treatment. For static movements, the phantom was alternately shifted 4.0 mm along the superior-inferior (SI) axis, -5.0 mm in the left-right (LR) axis and -5.0 mm in the anterior-posterior (AP) axis away from the isocenter. As shown in Figure 2, the phantom was shifted on the phantom rotation platform while the platform's axis of rotation remained aligned with the gantry isocenter at all times. For dynamic movements, the phantom rotation platform was placed on a 1D translation platform that moved the target periodically along the SI axis. The target was moved in a sinusoidal motion with a range of 10 mm (peak-to-trough) and a period of 6 s, replicating the range of lung tumor motion.[12]

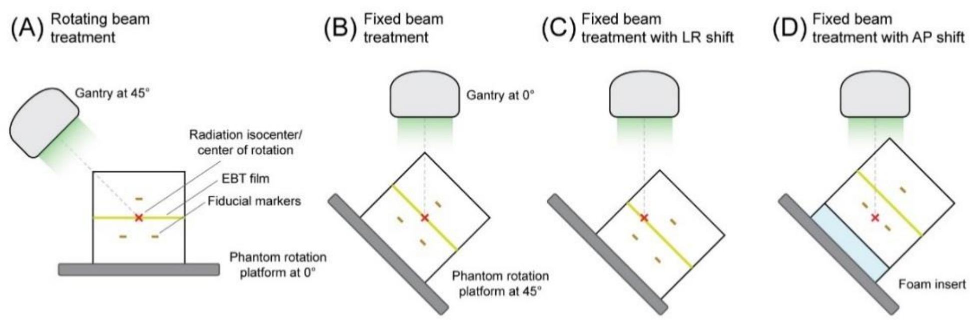

Fig 2. (A) and (B) shows irradiation of the phantom with the rotating beam and fixed beam treatment geometry respectively for a 45° beam angle. (C) and (D) shows the same irradiation with the phantom shifted in the LR and AP axes respectively. Motion in the SI axis are in and out of the page in this figure.

Kilovoltage Intrafraction Monitoring (KIM) was used to monitor the position of the target during treatment delivery. KIM is a marker based tracking algorithm that estimates the 3D position of a target based on 2D x-ray projections taken by the gantry-mounted OBI.[6] The

KIM workflow for a rotating beam and rotating OBI is described in detail in Keall *et al*.[13] For fixed beam treatments, KIM was adapted by replacing the gantry angle in the algorithm with the angle of the phantom rotation platform. As with a rotating beam treatment, a 3D probability density function (PDF) was obtained prior to treatment delivery. To obtain the PDF, fluoroscopic images are acquired at 11 Hz as the phantom is rotated in a 120° pre-treatment arc. The exposure parameters used were 80 kVp, 80 mA, 13 ms and a 6 × 6 cm^2 field size. Images continue to be acquired during treatment delivery as the phantom rotates to the angle for each IMRT field. The 3D position of the target is reconstructed in real-time by maximum likelihood estimation of the prior PDF.

To track the target, the target position from KIM is used as input to the MLC tracking algorithm that dynamically adapts the leaf positions of the 120-leaf Millennium MLC[9]. Based on this position and the angle of the phantom rotation platform, the leaf positions in the original treatment plan are modified to translate the beam aperture to the appropriate location. For dynamically moving target, a kernel density based prediction algorithm was applied to estimate the future position of the target after image acquisition[14]. The latency with which the updated leaf positions were sent to the MLC controller was measured to be 230 ± 20 ms. The effectiveness of KIM and MLC tracking for a target under rotation was measured by comparing the dose distribution about a shifted or dynamically moving target to the dose distribution delivered to a target at the isocenter.

2.D. Dosimetric Evaluation

The dose delivered to the phantom was measured using EBT3 film placed between two halves of the tumor target, perpendicular to the beam central axis at gantry 0°. Film analysis was performed by the method described in Devic *et al* [15]. Each piece of EBT3 film was

scanned prior to irradiation using an Epson V700 flatbed scanner (SEIKO Epson Co, Japan) in transmission mode with 48-bit RGB and a scanner resolution of 72 dpi. Following irradiation, the film was left for at least 24 hours and scanned with identical settings. The ratio of red channel pixel values from the pre-irradiated film to the irradiated film was calculated for each pixel. The optical density of each pixel was calculated by taking the $\log_{10}$ of this ratio. The optical density maps were smoothed using a Weiner filter with 3 × 3 pixel neighbourhood size, then related to dose using an optical-density-to-dose calibration curve obtained in the same measurement session. Dose values were normalized to the average value of a 5 × 5 mm^2 area surrounding the beam central axis. Dosimetric comparison between films was performed by analysing inplane and crossplane dose profiles and by performing a 2D gamma analysis using a 2%/2 mm criteria for areas of the film receiving greater than 20% of the maximum dose.

3. RESULTS

3.A. Dosimetric equivalence between rotating beam and fixed beam treatments

Figure 3 shows the inplane and crossplane dose profiles of the fixed beam treatment compared to the rotating beam treatment and the treatment planning system. For these measurements, the target was located at the isocenter and motion tracking was not used. Gamma analysis between the two films showed 100% pass rate using a 2%/2mm criteria. These results demonstrate dosimetric equivalence between these two treatment geometries for a target located at the isocenter.

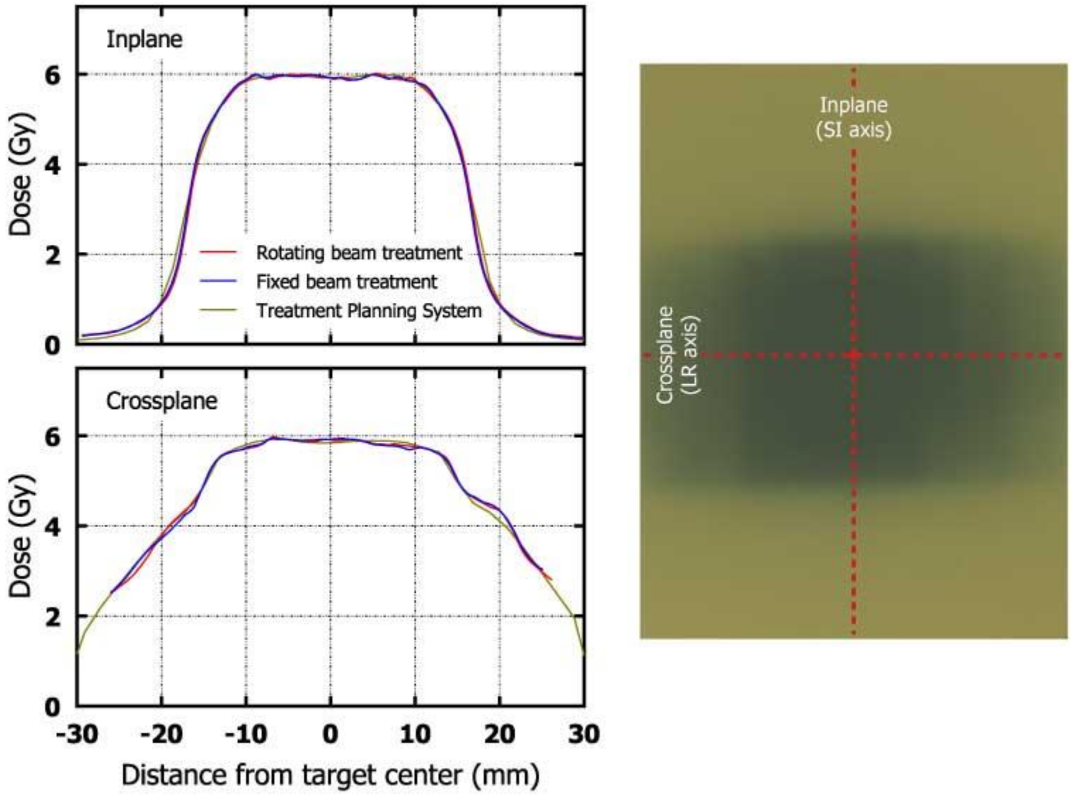

Fig 3. Dose profiles of the rotating beam and fixed beam IMRT treatments measured using EBT3 film and compared to the treatment planning system. Inplane and crossplane profiles were taken through the isocenter along the SI and LR axis respectively, as shown on the film image.

3.B. MLC tracking for static phantom shifts

Figure 4 shows dose profiles of a fixed beam treatment where the tumour target is moved 5mm away from its original isocentric position to simulate target motion during rotation. Without motion tracking, these shifts manifest as offsets in SI shifted inplane dose profile and the LR shifted crossplane dose profile and as lower dose for the AP shifted profiles. KIM reported average shifts of 4.03 ± 0.10 mm, -4.89 ± 0.32 mm and -4.80 ± 0.17 mm in the SI, LR and AP axes respectively.

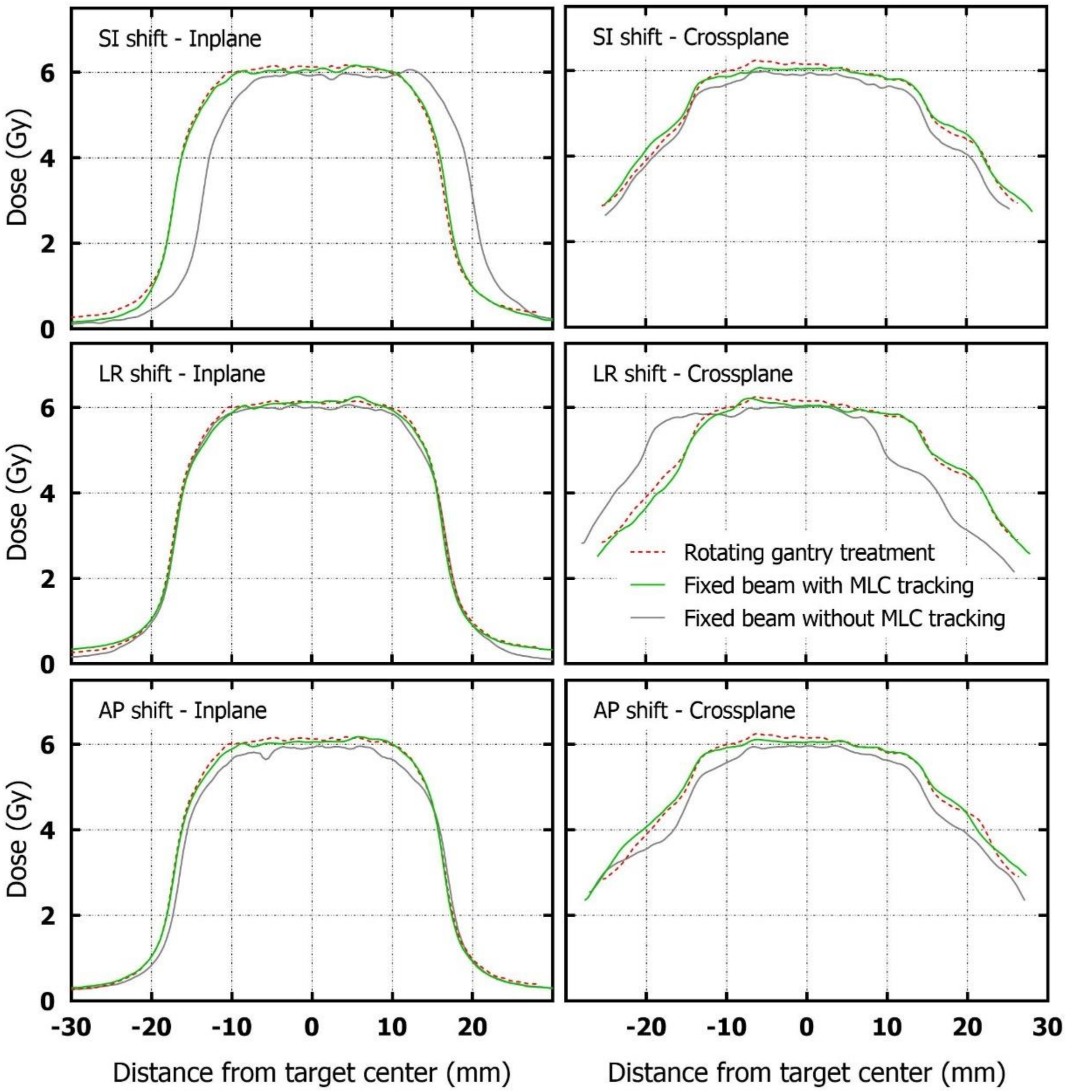

Fig 4. Inplane and crossplane dose profiles for fixed beam IMRT treatments with and without MLC tracking to compensate for shifts in the phantom's position in the SI, LR and AP directions. Dose profiles are compared to a rotating gantry treatment where the target is located at the isocenter.

When KIM and MLC tracking are used, the dose profiles around the shifted targets visually show good agreement with the dose profiles delivered to the target at isocenter. This indicates that MLC tracking has successfully compensated for these movements as the phantom is rotated and the dose distribution about the target is maintained.

Gamma analysis of the dose distributions achieved with KIM and MLC tracking showed high pass rates using the 2%/2mm criteria. When compared to a rotating beam treatment where the target is positioned at the isocenter, the pass rates were 100%, 99.4% and 99.8% respectively. When compared to a fixed beam treatment where the target is positioned at the isocenter, the pass rates for the SI, LR and AP shifted targets were 99.0%, 99.3% and 99.8% respectively.

3.C. MLC tracking for dynamic motion

Figure 5 shows the dose profiles when KIM and MLC tracking are used to follow a target moving with a periodic motion in the SI direction. For both rotating beam and fixed beam geometries, the dose profiles with MLC tracking show good agreement with the dose profile of a static treatment. Gamma analysis of the dose distributions compared to the static case had pass rates of 98.7% and 99.7% for the rotating beam and fixed beam geometries respectively, using the 2%/2mm criteria. This demonstrates the effectiveness of MLC tracking as the same treatment delivered without MLC tracking would have resulted in a pass rate of 90.1%.

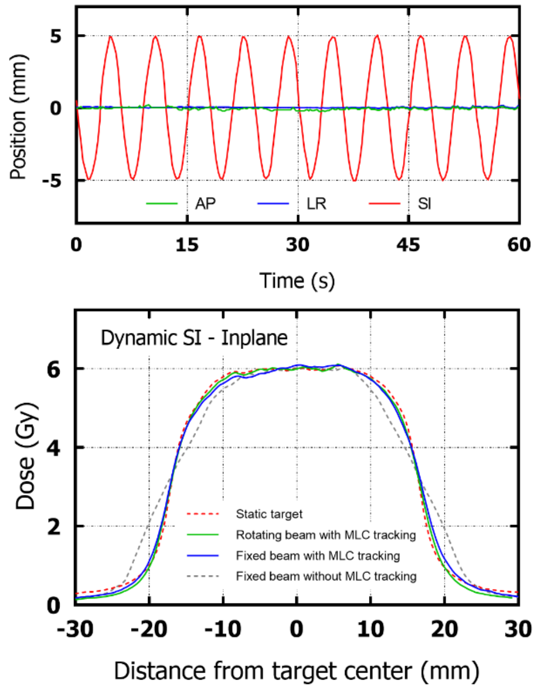

Fig 5. Top: the position of the marker centroid measured by KIM for the dynamically moving target under rotation. Bottom: inplane dose profile of the rotating beam and fixed beam IMRT treatments utilizing KIM and MLC tracking to compensate for periodic motion along the SI axis. Dose profiles are compared to the static case without target motion and dynamic case with the same motion, delivered with a rotating gantry geometry.

The use of MLC tracking reduces the broadening of the beam penumbra that occurs as a result of tumour motion and can cause under-dosing of the target. Without motion compensation, the average width of the beam penumbra (80%-20%) along the axis of motion increases from 4.7 mm to 9.3 mm due to target motion. When MLC tracking is used, the width of the penumbra is 5.2 mm in the case of a rotating gantry treatment and 5.9 mm in the case of the rotating target treatment.

4. DISCUSSION AND CONCLUSION

In this work, we have demonstrated two properties of fixed beam radiotherapy. First, the dose distribution of a fixed beam treatment where the target is rotated is equivalent to that of a conventional treatment delivered using a rotating beam. Second, through the use of real-time target localisation (KIM) and beam adaptation (MLC tracking) algorithms, the desired dose distribution can be maintained even if a target moves with rotation. These properties represent a proof-of-principle for image-guided fixed beam radiotherapy.

The image guidance technologies described in this work are well-suited for a compact fixed beam system as they are primarily a software solution. No specialised hardware is required for its implementation other than the kV imager and MLC found on a conventional linac which allows the system to remain cost-effective. Furthermore, a treatment system built around image guidance can increase the role of automation in radiotherapy. By using image guidance to reduce the stringency of patient alignment and position verification, the time and staff burden of patient set-up can be reduced.

The concept of patient rotation, however, brings additional challenges to fixed beam treatments. In the case of horizontal rotation, there will be gravity induced motion in a patient's anatomy as they are rotated to different angles, causing changes in the position of the target and surrounding organs[16]. Barber *et al* [17] found in x-ray images of anesthetised rabbits under horizontal rotation that organ motion due to gravity was of similar magnitude to organ motion due to respiration. Though intrafraction motion could be managed within the ICRU framework with a margin expansion, we have demonstrated that the real-time image guidance and beam adaptation can more eloquently achieve similar accuracy. In order to achieve a suitable level of clinical accuracy in the presence of gravity induced motion, the

real-time beam adaptation techniques described in this work should be integrated for all treatments on this type of device.

The benefit of this approach is that the inherent advantages of image guidance will improve the overall safety and quality of the treatment. In a fixed beam radiation system, gravity induced motion will be combined with usual physiological motion such as respiratory or gastrointestinal motion. The use of MLC tracking (which has been successfully trialled in patients for a rotating beam geometry[10,18] and shown here to successfully track phantom movement for a fixed beam geometry) can be used simultaneously compensate for both sources of motion. These treatments can clinically benefit from the ability to reduce the size of clinical margins and the improved dose homogeneity within the target volume[19].

The scaling of the image guidance techniques in this work from a small phantom to a full-size fixed beam treatment system capable of treating human patients presents some unique challenges.. For patients rotated horizontally, gravity induced motion would need to be accounted for during imaging[20], simulation and treatment delivery to bring this treatment method into clinical practice. New upright imaging techniques also enable patients to be rotated along the vertical axis, where less motion would be expected[21]. Further development will also be required to achieve a fully motion adaptive treatment that includes corrections for target deformation and changes to nearby organs at risk as well as dose recalculation.

A prototype fixed beam linear accelerator with a full-size patient rotation system has been installed at the Nelune Comprehensive Cancer Centre in Sydney, Australia[22] and is undergoing development. This full-size fixed beam device will implement the image guidance techniques described in this work to form a treatment system capable of delivering

highly precise radiotherapy treatments with the elevated clinical benefits of image guidance, but on a simpler and more cost-effective device.

ACKNOWLEDGEMENTS

The authors thank the department of radiotherapy within the Northern Sydney Cancer Centre for their generous support of this work through the use of clinical equipment. The authors thank Scott Johnson at Varian Medical Systems for enabling a research licence for MLC tracking on Trilogy. This work is funded by an Australian NHMRC Development grant. P J Keall is funded by an NHMRC Senior Principal Research Fellowship. D T Nguyen acknowledges funding from a NHMRC Early Career Fellowship and a Cancer Institute New South Wales Early Career Fellowship.

DISCLOUSRE OF CONFLICTS OF INTEREST

Co-author Keall is an inventor on several pending patents related to KIM and MLC tracking. Co-authors Feain and Keall are inventors on several pending patents Nano-X technology and are founders and shareholders of Leo Cancer Care Pty Ltd, which is developing a fixed beam radiotherapy system. Leo Cancer Care Pty Ltd has licensed intellectual property from the University of Sydney.

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