Radiotherapy and Oncology xxx (2017) xxx–xxx

Contents lists available at ScienceDirect

Radiotherapy and Oncology

journal homepage: www.thegreenjournal.com

Original article

Experimental verification of dose enhancement effects in a lung phantom from inline magnetic fields

Bradley M. Oborn [a,b,*], Maegan A. Gargett [c,b], Trent J. Causer [a,b], Sarah J. Alnaghy [b,e], Nicholas Hardcastle [d,b], Peter E. Metcalfe [b,e], Paul J. Keall [f,e]

[a] Illawarra Cancer Care Centre, Wollongong; [b] Centre for Medical Radiation Physics, University of Wollongong; [c] Northern Sydney Cancer Centre, St Leonards; [d] Peter MacCallum Cancer Centre, Melbourne; [e] Ingham Institute for Applied Medical Research, Liverpool; and [f] Sydney Medical School, University of Sydney, Australia

ARTICLE INFO

Article history:
Received 31 May 2017
Received in revised form 14 September 2017
Accepted 15 September 2017
Available online xxxx

Keywords:
MRI guided radiotherapy
Lung dose enhancement
Magnetic fields

ABSTRACT

Background and purpose: To present experimental evidence of lung dose enhancement effects caused by strong inline magnetic fields.
Materials and methods: A permanent magnet device was utilised to generate 0.95 T–1.2 T magnetic fields that encompassed two small lung-equivalent phantoms of density 0.3 g/cm^3. Small 6MV and 10MV photon beams were incident parallel with the magnetic field direction and Gafchromic EBT3 film was placed inside the lung phantoms, perpendicular to the beam (experiment 1) and parallel to the beam (experiment 2). Monte Carlo simulations of experiment 1 were also performed.
Results: Experiment 1: The 1.2 T inline magnetic field induced a 12% (6MV) and 14% (10MV) increase in the dose at the phantom centre. The Monte Carlo modelling matched well (±2%) to the experimentally observed results. Experiment 2: A 0.95 T field peaked at the phantom centroid (but not at the phantom entry/exit regions) details a clear dose increase due to the magnetic field of up to 25%.
Conclusions: This experimental work has demonstrated how strong inline magnetic fields act to enhance the dose to lower density mediums such as lung tissue. Clinically, such scenarios will arise in inline MRI-linac systems for treatment of small lung tumours.
 Radiotherapy and Oncology xxx (2017) xxx–xxx

Real-time MRI-guided radiotherapy treatments have been delivered for over two years through the ViewRay system [1]. Patient treatments on the Unity 1.5 T MRI-linac system are planned before the end of 2017 [2]. In both of these systems the magnetic field of the MRI scanner is perpendicular to the X-ray beam direction. This leads to various dose changes, with respect to the no magnetic field case, that need addressing such as the electron return effect (ERE) [3]. In terms of basic dose planning calculation quantities, a transverse magnetic field sets up an asymmetric tilting of the secondary electron dose kernel due to the Lorentz force. This tilting becomes stronger as magnetic field strength increases [4], and the ERE can be considered as an artefact of this process that occurs at boundaries between different density mediums. Recent modelling work has shown successfully however that these effects, with appropriate planning, should be negligible in the Unity system for lung stereotactic body radiotherapy treatments [5].

In two other non-clinical prototype MRI-linac systems, the Aurora-RT [6], and the Australian MRI-linac [7], the magnetic field is parallel or inline with the X-ray beam direction. In these two prototype systems it could be expected that the inline orientation design was envisaged as a solution to the ERE. To be more specific, in this orientation the magnetic field acts to slightly lengthen the dose kernel in the forward direction. In water, this leads to very minimal differences between 1 T and 0 T. However in much lower density mediums such as lung, there is a stronger stretching of the dose kernel in the forward direction. This also narrows the width of the dose kernel, and so sets up a small increase in intensity in the forward direction. Basic superposition of these kernels, to estimate the dose from a small X-ray beam, will result in beams with narrower penumbral widths and slightly stronger doses. The concept of generating a more conformal dose distribution by applying inline magnetic fields has been investigated previously for X-ray beams in water phantoms using both simulations and experiments [8–10]. The first basic simulation work however on changes in lung tissue doses due to inline magnetic fields was reported in 2010 [11]. More recent work studied the impact of a 1 T inline magnetic field on 8 clinical small lung tumour cases planned with 6MV 3D-CRT treatments [12]. A compelling prediction of this modelling

* Corresponding author at: Locked Mail Bag 8808, South Coast Mail Centre, NSW 2521, Australia.
E-mail address: brad.oborn@gmail.com (B.M. Oborn).

https://doi.org/10.1016/j.radonc.2017.09.012
0167-8140/

work was that the mean dose to the PTV could be enhanced by as much as 22% when the magnetic field was included, for small lung tumours around <3 cc in volume. We do note however a high skin dose induced in the Australian MRI-linac system [13,14], which is not reported in the Aurora-RT system [15]. In general, the advantages of the inline systems over the perpendicular systems is the improved patient dosimetry (no ERE), however this comes at the cost of rotating the magnet around the patient (Aurora-RT) or rotating the patient (Australian MRI-linac). For a more in-depth summary of the benefits and disadvantages of the various MRI-linac systems we refer the reader to Table 2 in Keall et al. [7].

In this work, we report experimental evidence of the dose changes observed in a lung phantom when surrounded by strong inline magnetic fields of 0.95 T–1.2 T.

Materials and methods

Permanent magnet system

A portable permanent magnet based system was used to generate a strong magnetic field over a small volume. This system is shown in Fig. 1. Two banks of NdFeB permanent magnets are held in a steel yoke with focusing cones to concentrate the magnetic flux across the pole gap. Holes of $5 \times 5\ cm^2$ in cross-section in the magnet banks and steel yoke allowed for the X-ray beam to be incident inline with the magnetic field. The two experimental setups are shown in Fig. 1. In experiment 1, a 3 cm gap between the cone tips exists and the magnetic field generated directly across the gap is peaked at 1.2 T. In this case, the 6 cm thick steel cone tips contain a 0.5 cm wide split along the central axis to allow the radiation beam to pass through.

In experiment 2, the cone tip gap is also 3 cm however a $2.5 \times 2.5\ cm^2$ hole exists in the middle of the cones. This allows for X-ray beams of $2 \times 2\ cm^2$ to pass through the device uninterrupted. The magnetic field generated across the gap is peaked at 0.95 T.

Phantom setup and film measurements

Phantom 1 consisted of a $7.5 \times 5\ cm^2$ piece of Gafchromic EBT3 film sandwiched between two pieces of lung equivalent phantom. The two phantom pieces were $5 \times 7.5 \times 2\ cm^3$ and $5 \times 7.5 \times 1\ cm^3$ in size. Phantom two consisted of a $15 \times 2.4\ cm^2$ piece of EBT3 film sandwiched between two lung phantoms blocks of size $1.2 \times 2.4 \times 15\ cm^3$.

The EBT3 films were calibrated following the methods outlined by Devic et al. [16] using a standard single-channel analysis procedure (red channel) to convert net optical density to dose, for a dose range of 0–5 Gy. Films were scanned on an EPSON (10000XL) flatbed scanner with 150 dpi resolution. The average of 3 scans were used for analysis. The estimated standard uncertainty associated with these measurements is ±3%.

Phantom irradiation with magnetic field

The magnet device was positioned such that the source to magnet isocenter was 150 cm for all measurements. This distance is designed to approximately match the source-to-isocenter distance (SID) of the Australian MRI-linac system [14]. The fringe field of the magnet was measured to be <2 Gauss at 1 m from isocenter and so deemed not to have any impact on the output of the Linac (Varian Clinac 2100C). 6MV and 10MV beams of field size (at 150 cm SID) $3 \times 3\ cm^2$ (experiment 1) and $1.4 \times 1.4\ cm^2$ and $2.0 \times 2.0\ cm^2$ (experiment 2) were delivered to the lung phantoms.

Phantom irradiation without magnetic field

All experiments performed within the magnet were repeated without the magnetic field. In these reference zero-field conditions, the same focusing cones were used to hold the phantoms in a replica arrangement. The steel focusing cones were held in the same position as the in-magnet positions using an aluminium frame. Hence the entire steel circuit is not present but only the important steel surrounding the phantom. This ensures that the identical scattering conditions surrounding the phantoms are preserved when compared with the case that included the magnetic field.

Monte Carlo simulation

Geant4 version 10.1 was used to simulate the experiment 1 setup as an independent cross-check of the results observed with film (Fig. 2). In this simulation the X-ray beam was modelled from reading phase space files of matching small fields. These were generated using an existing in-house Monte Carlo system that has been benchmarked and reported elsewhere [17]. Geometry was setup that matched the permanent magnet device, and a full 3D magnetic field map was introduced into the simulation. This was generated by finite element modelling (COMSOL), and the volume encompassed included the entire magnet device. Thus particle tracking considers an accurate representation of the experimental setup and surrounding magnetic field. Dose was scored in a volume that matched the film shape and location. The virtual film pixel resolution was 1×1 mm, and the film thickness was modelled as being 0.25 mm. For each simulation a total of 1×10^8 particles were fired from the phase space (94.2 cm above isocenter of the magnet). 10 parallel simulations were run and the results merged

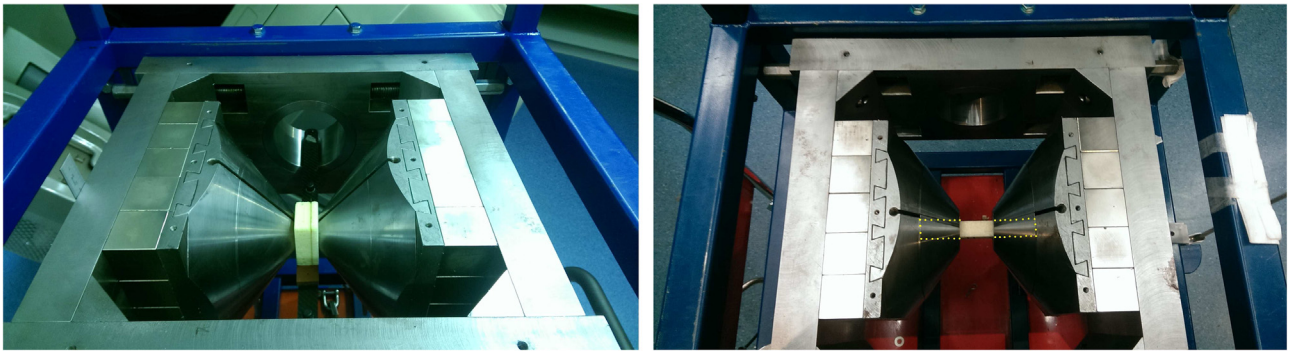

Fig. 1. Experimental setup. Left: experiment 1 contains a $5 \times 7.5 \times 3\ cm^3$ lung phantom with film insert. Right: Experiment 2 contains a $2.4 \times 2.4 \times 15\ cm^3$ lung phantom with film placed along the beam central axis and inside the cone tip holes. An outline of the lung phantom is shown superimposed.

Please cite this article in press as: Oborn BM et al. Experimental verification of dose enhancement effects in a lung phantom from inline magnetic fields. Radiother Oncol (2017), https://doi.org/10.1016/j.radonc.2017.09.012