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Development of a methodology to study the effect of magnetic field on dose distributions in an MR-linac, using PRESAGE® and Monte Carlo calculations

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Abstract. At the Royal Marsden Hospital (RMH) and the Institute of Cancer Research (ICR) a new MR-linac is being installed and commissioned. Modifications to absorbed dose patterns will occur, because the paths of secondary electrons are deflected by Lorentz forces. In this paper, we describe a methodology to measure the effects of magnetic field on dose distributions, using the PRESAGE® 3D dosimeter and Monte Carlo (MC) simulations. A poly(methyl methacrylate) (PMMA) phantom has been developed to be positioned between the poles of an electromagnet and accommodate cylindrical samples of PRESAGE®. This phantom will be used to study the influence of different magnetic field strengths on radiation deposition from a Cobalt-60 (^{60}Co) beam. Both the orientation of the samples with respect to the magnetic field and radiation beam, and the size of the air gap can be changed. Preliminary MC simulations with two PRESAGE® cylinders separated by an air gap, gave a good insight about the dosimetric effects that can be obtained with our newly-developed phantom.

1. Introduction

One of the world's first combined MRI and linear accelerator (MR-linac) systems is currently being installed and commissioned at the Royal Marsden Hospital (RMH) and the Institute of Cancer Research (ICR). As part of an international consortium to develop the technology, our aim is to provide image guidance during treatment by acquiring MR images of patients, with high soft-tissue contrast.

The MRI system (Philips, Hamburg, Germany) is similar to a standard clinical scanner, but with the main magnetic field generated by a specially-designed, "split" 1.5 T magnet, with no gradient or static magnetic field (B0) coils in a central region through which radiation passes. A 7 MV linear accelerator (Elekta, Crawley, UK), with multileaf collimator, will rotate in a ring around the outside of the magnet.


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A significant challenge in the delivery of radiotherapy by the MR-linac is the altered behaviour of secondary electrons. As the main magnetic field is always on, Lorentz forces will act perpendicularly to the direction of the electron travel and thus deflect the path of the cascade of secondary electrons [1]. This is particularly relevant at tissue-air boundaries where an electron return effect (ERE) is visible as electrons are forced back to the tissue, creating an increase in dose near the boundary. The effect is also dependent on the orientation of the entrance and exit surfaces with respect to the MRI static magnetic field [2]. Build-up distance is reduced and this could also create high surface doses.

Treatment planning systems have been specially developed to account for these effects [3]. However, accurate dosimetric characterization is essential to validate and commission this new technique before clinical implementation. Performing 2D data measurements of individual beams to validate IMRT treatment plans has been shown to be prone to inaccuracies [4]. Effects of magnetic field are likely to contribute to the increased complexity of dose distributions on an irradiated volume, emphasizing the need for accurate high resolution 3D dosimetric evaluation [5].

The aim of this paper is to define a methodology to study the effect of magnetic field on dose distributions, using the PRESAGE® 3D dosimeter [6] when air gaps are present. Preliminary Monte Carlo (MC) simulations are reported to test this experimental set-up.

2. Material and Methods

2.1. Phantom development and experimental set-up

A PMMA phantom was developed to accommodate cylindrical samples of PRESAGE® (Heuris Pharma, Skillman, NJ) of 2 cm diameter and a maximum of 7 cm length (figure 2B). Two pieces of PRESAGE® can be placed inside the phantom, separated by an air gap of variable size. The phantom can also be oriented in 3 different positions in relation to the beam (figure 1). The PMMA phantom consists of a number of separate ($5 \times 5 \times 1$ cm^3) slabs that can be assembled together and provide electronic equilibrium, with a density very similar to that of PRESAGE®. The black acetal base was created to fit a sample holder developed at the UK's National Physical Laboratory (NPL, Teddington, UK) for positioning ionization chambers in the magnetic field.

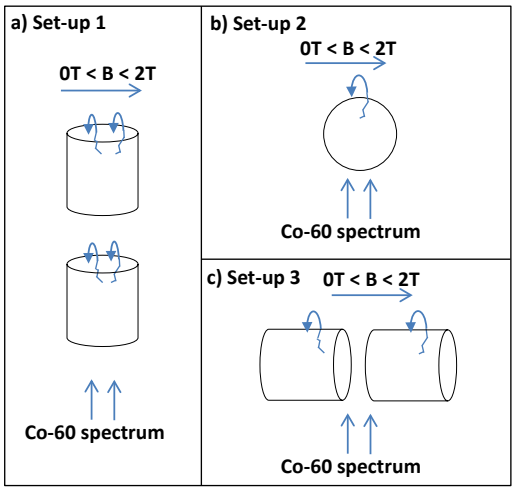

Figure 1. Three different PRESAGE® orientations that can be set-up using the PMMA phantom between the pole pieces of the electromagnet, to study the effect of an air-gap size, orientation and consequences of changing the magnetic field strength. The curved blue arrows represent schematically the electron paths under the influence of the Lorentz force.

Prior to the MR-linac itself coming into service, the phantom is placed in an electromagnet which allows us to study the effects on dose distribution under different magnetic field (B) strengths. At NPL, an electromagnet (250MM Electromagnet, GMW, San Carlos, USA) has been installed next to a ^{60}Co unit (Theratron 780C, Theratronics, Ontario, Canada). The distance between the poles of the electromagnet can be varied, but for this study, the configuration used had a 5 cm gap, giving an accessible range of magnetic field strength of 0 T – 2 T by varying the current intensity. The distance from the source to the centre of the magnetic poles was set to be 162 cm.

A schematic of three possible PRESAGE® set-up orientations is shown in figure 1. In the first figure1 (a), the long axis of the PRESAGE® is parallel to the beam direction, with an air gap in the middle. At the entrance of the first PRESAGE®, a shifted depth of dose maximum (dmax) is expected. A 4 mm shift to the left of the profile was reported for a 6 MV photon beam [2]. An increase on the dose is also expected on the distal side of both PRESAGE® cylinders due to the ERE. For this reason, electrons coming from the first PRESAGE® do not cross the air cavity, and, a new build up curve should appear at the beginning of the second PRESAGE®, as electron equilibrium has to be established again. When the magnetic field is off, a slight rebuild up is still expected due to the lack of lateral electron equilibrium. In the other configurations (figures 1(b) and 1(c)), the dose increase is expected on the exiting lateral side of both PRESAGE® cylinders. The experimental arrangement at NPL is shown in figure 2A.

2.2. Optical CT

Samples will be imaged using an upgraded version of the optical CT microscopy scanner described in [7], which has a maximum field-of-view of 2.5 cm.

2.3 Monte Carlo (MC) Simulations

EGSnrc/Cavity, a C++ user-code advanced EGSnrc application, was used to simulate the experimental set-up. A phase-space file of the Theratron numerical model has been previously implemented in BEAM, an EGSnrc-based MC code, at NPL for reference conditions (SSD=95cm, 10×10 cm^2 field). This phase-space file was used as the source on the EGSnrc/Cavity simulation, after modifying the jaws and the distance from the source to the centre of the poles, to be representative of the new set-up.

Simulations of two PRESAGE® cylinders with their long axes parallel to the beam and a 1.95 cm air gap in between them were performed with and without 1.5 T magnetic field [8]. Percentage depth dose (PDD) profiles were obtained for the first of the set-up orientations shown in figure 1(a).

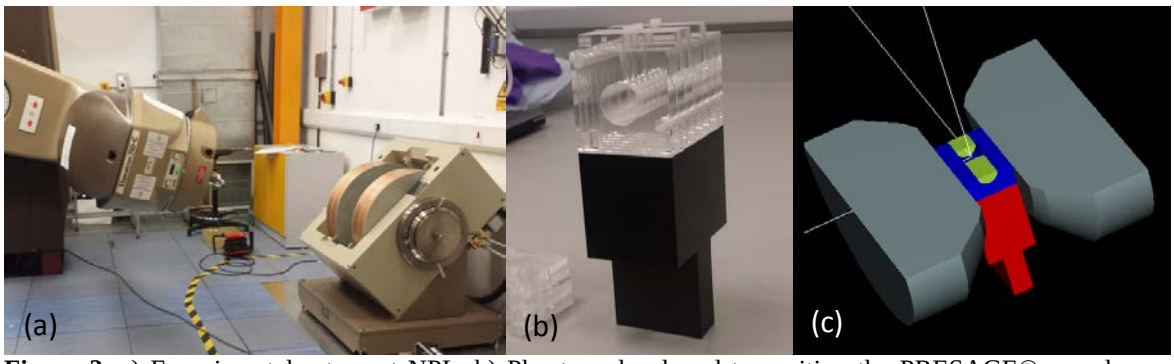

Figure 2. a) Experimental set-up at NPL. b) Phantom developed to position the PRESAGE® samples on the electromagnet. c) Axial cut of the simulated geometry displayed with C++ geometry viewer, EGS view.

3. Results and discussion

Preliminary simulations with and without the 1.5 T magnetic field are shown in figure 3 and demonstrate a dose increase of more than 40% at the beam exit of both samples due to the ERE. However, the expected reduction of dmax depth is not present. This effect may not be noticeable for the Co-60 as the beam has lower energy than the 6MV beam. Additionally, the build-up region may be modified by the increased dose effect due to the pole pieces of the electromagnet. More simulations need to be performed to answer these questions.

The pole pieces were found to contribute to an increase of approximately 8% on the PRESAGE® dose. This is likely to be due to the lateral scatter radiation coming from the pole pieces. In addition to the dose increase, when the pole pieces are simulated, a higher dose is observed at the end of the first PRESAGE® and beginning of the second PRESAGE®. This is not fully understood and further investigation is still required.

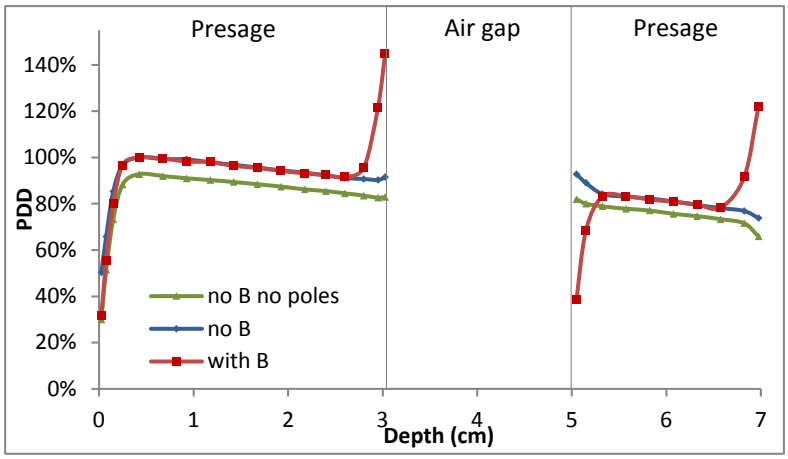

Figure 3. Preliminary results obtained by taking a central profile along the length of the two PRESAGE®s (figure 1(a), figure 2 (c), which have a 1.95cm air gap between them. Simulations were performed with and without magnetic field (B).

Work published very recently in thesis form [9] has addressed a number of issues related to this work. Its author encountered a number of problems associated with the optical-CT readout of a PRESAGE® sample with a hole in the middle. With our newly-developed phantom, it should be possible to mimic the simulated arrangement and study the effect of ERE in the presence of air gaps by scanning independently two PRESAGE® cylinders without such severe refraction-related artefacts. Furthermore, the ability to vary the air gap, the magnetic field strength and the interface orientation with respect to the magnetic field and beam entry will allow us to compare our experimental data with a wider variety of simulation results, thus resulting in a better understanding of the ERE.

It is likely, however, that the effect of an interface between PRESAGE® and the matching liquid (used to reduce the refractive index mismatch between the sample and its surroundings) will still need to be corrected in order to achieve accurate quantitative results in the build-up regions. This will be an important area of future study.

4. Conclusion

This preliminary study provided good insight about the dose distributions we expect to obtain with PRESAGE® cylinders, separated by an air gap, and in the presence of strong magnetic fields. However, some dose effects still need further investigation. Future 2D and 3D simulations of the set-up orientations described above will be used to compare with the optical-CT reconstructed images of the samples.

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