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Original paper

Experimental evaluation of the impact of low tesla transverse magnetic field on dose distribution in presence of tissue interfaces

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ABSTRACT

Purpose: Aim of this study is to experimental evaluate the impact of a 0.35 T transverse magnetic field on dose distribution in presence of tissue-air and tissue-lung interfaces.

Methods: The investigation was carried out using MRIdian (ViewRay, Cleveland, Ohio) and it consisted of comparing experimental measurements performed by Gafchromic EBT3 film dosimetry, to Montecarlo simulations, carried out in the presence and, as well as, the absence of the magnetic field.

A preliminary dose calibration was planned on MRIdian, arranging $3 \times 3\,cm^2$ film pieces in a water slab phantom and exposing them at different beam-on times, in a dose range equal to 0.1–12.1 Gy.

All experimental measurements were then carried out using the calibrated films and delivering one single beam orthogonally to three different phantoms: without inhomogeneity, with an air gap and with a lung inhomogeneity.

The dose distributions measured by EBT3 films in presence of magnetic field were compared to those calculated in the presence and, as well as, the absence of the magnetic field, in terms of gamma analysis. A quantification of electron return effect (ERE) was also performed.

Results: All the tested plans considering the magnetic field show a gamma-passing rate higher than 98% for 3%/3 mm gamma analysis.

In presence of tissue-air interface, the electron return effect causes an over-dosage of +31.9% at the first interface and an under-dosage of −33% at the second interface. The dosimetric variations in presence of tissue-lung interface results to be smaller (+0.8% first interface, −1.3% second interface).

Conclusion: The impact of 0.35 T magnetic field is not negligible and it can be effectively modelled by the Montecarlo dose calculation platform available in the MRIdian TPS.

1. Introduction

Magnetic resonance guided radiotherapy (MR-gRT) today represents one of the most promising techniques in the framework of personalised cancer care, offering high-quality soft tissue contrast imaging and precise radiation delivery [1,2].

The hybrid systems designed for MR-gRT combine an RT delivery unit with a Magnetic Resonance Imaging (MRI) scanner, and they differ on the basis of the geometry system and the magnetic field strength.

The two systems currently available for clinical practice use a transverse geometry system where the radiation source is mounted so as to irradiate between the two poles of a cylindrical coil magnet system and the magnetic field (B_0) force lines are transversely oriented with respect to the radiation beam. Unity (Elekta, Stockholm, Sweden) uses a 1.5 T MRI scanner with a 6 MV Flattening Filter Free (FFF) Linac, while MRIdian (ViewRay, Cleveland, Ohio) joins 0.35 T MRI scanner with

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three ^{60}Co γ-ray sources or a 6 MV FFF Linac for radiation delivery [3,4].

Systems implementing longitudinal geometry are currently under development, where the central axis of the radiation source is oriented parallel to the magnetic field force lines, as the Aurora-RT™ Linac-MR developed by the MagnetTx Oncology systems [5,6].

One of the principal concerns related to the hybrid technologies is represented by the impact of the magnetic field on dose distribution, as the electrons produced by the interaction of the radiation with the patient tissues are subjected to the Lorentz force [7,8].

It has been established that the magnetic field causes a more significant perturbation in systems with transverse design and the entity of such perturbation on the photon beam irradiation increases with higher magnetic field strength [9,10].

In presence of a transverse magnetic field, the radiation beam experiments changes in the percentage depth dose, lateral shift of the dose distribution and dose variations at the interfaces between different medium densities, such as air-tissue or lung-tissue.

In these last cases, the electrons leaving the tissue can describe a 180-degree trajectory due to the Lorentz force, coming back to the original tissue and causing therefore a local dose increase [11].

This phenomenon, known as electron return effect (ERE) can cause a dose increase at the first interface (between tissue and low-density medium) and a consequent dose decrease at the second interface (between low-density medium and tissue) as most electrons interacted at the first interface. The ERE effect is significantly reduced or eliminated in longitudinal systems, where the magnetic field restricts the radial spread of secondary electrons, focusing these electrons on the beam axis [6,10,12].

Due to the limited diffusion of the hybrid systems, the B effects on the photon beam irradiation have been mainly studied by using Montecarlo simulations and a limited number of works have supported the numerical simulations with experimental measurements, principally focused on high tesla systems [6,9,10,13,14].

Considering the recent diffusion of these technologies in the clinic, the need arises to experimentally quantify the magnitude of dose variations due to the B presence and to evaluate the agreement between Montecarlo simulations and experimental measurements.

The aim of this study consists in experimentally estimating the impact of a 0.35 T transverse magnetic field on dose distribution in presence of tissue-air and tissue-lung interfaces. The investigation consisted of comparing experimental measurements performed in presence of magnetic field by radiochromic film dosimetry, to Montecarlo simulations, carried out in the presence and, as well as, the absence of B_0.

The experimental measurements were realised using Gafchromic EBT3 films: the use of these detectors in presence of magnetic field has already been addressed by Reynoso et al., who demonstrated that these dosimeters are influenced by the magnetic field, but that this influence can be overcome by calibrating the films directly in magnetic field [15].

Thanks to their reduced thickness and high spatial resolution, these films are suitable to perform measurements in presence of interfaces, where the ionisation chambers experiment different issues due to lack of charged particles equilibrium [16]. They were already used to estimate dose distributions at tissue-air interfaces in absence of magnetic field and they were also considered as reference to compare different calculation algorithms [17].

2. Materials and methods

2.1. Film calibration

A dose calibration step was planned in the Cobalt-60 version of MRIdian to perform absolute dose measurements by using Gafchromic EBT3 films.

Films were cut in 3 × 3 cm^2 pieces and arranged in a water slab phantom (mass density ρ = 1.032 g/cm^3, Solid Water HE, Gammex, Middleton, Wisconsin, USA), 5 cm deep from the phantom surface. A 15 cm solid water layer was placed below the Gafchromic film to provide backscattered radiation. Films were exposed perpendicularly to the beam axis and placed at the source to detector distance (SDD)that is equal to 105 cm.

The calibration step consisted of 13 film pieces irradiated at different exposure times in the range of 15–460 s (corresponding to dose range 0.1–12.1 Gy) by a 10 × 10 cm^2 beam placed a 0 degree. All the films used belonged to the batch #06071602.

An absolute dose measurement was performed contextually to the calibration step by placing an MR-compatible ionisation chamber (Semiflex 30006, PTW, Freiburg, Germany), in the same setup adopted for film calibration (SSD = 100 cm, SDD = 105 cm), and aligning the major axis of the detector to the magnetic field force lines.

The ionisation chamber was exposed for 60 s to a 10 × 10 cm^2 beam placed a 0 degree and the relation between beam on time and dose delivered was then calculated. The dose value was determined following the IAEA TRS 398 protocol [18].

The flatbed scanner EPSON Expression 11000XL (Seiko Epson Corp, Nagano, Japan) was used to digitise the films. The film pieces were digitised in transmission mode using an image resolution of 150 dots per inch and saved in 48-bit RGB modality, according to the recommendations highlighted in different experiences on Gafchromic use [16,19].

Each film was digitised before and 24 h after the irradiation. Digitisations were carried out by placing the film in the most uniform scanner region and acquiring the whole scanner area, in order to minimize the impacts of scanner noise.

Digitised images were analysed using the ImageJ software (v1.39, National Institutes of Health, Bethesda, MD). The mean pixel values before and after irradiation in a 1 × 1 cm^2 central Region Of Interest (ROI) (PV_{unexp} and PV_{exp}, respectively) were calculated for the red and green channel, and the sum signal (SS) value was then calculated, according to the Eq. (1):

$$SS = log_{10}\left(\frac{PV_{unexp}}{PV_{exp}}\right)_{RED} + log_{10}\left(\frac{PV_{unexp}}{PV_{exp}}\right)_{GREEN} \quad (1)$$

The experimental data obtained during the calibration step were fitted using a double exponential function [20]:

$$D(SS) = a*exp(b*SS) + c*exp(d*SS) \quad (2)$$

2.2. Experimental measurements

All experimental measurements were carried out in presence of 0.35 T magnetic field using the MRIdian system and delivering a single beam placed at 0 degree, orthogonally to the magnetic field force lines and to different phantoms and placing Gafchromic EBT3 films inside the phantoms.

A helical CT scanner (HiSpeed DX/i Spiral, General Electrics, Fairfield, Connecticut, USA) was used to acquire an image of the phantoms involved in this study, in order to obtain the electron density information required for treatment plan calculation.

The dose distributions were calculated using the MRIdian Treatment Planning System (TPS) (v. 4.5.1.239) implementing a Graphical Power Unit (GPU)-accelerated Montecarlo dose calculation platform, based on the PENELOPE code and widely diffused in the clinical practice of MR-guided RT [21].

A total of 2.4 million of histories were considered in the Montecarlo calculation and the dose resolution grid was set at 1 mm. Gafchromic films were always managed and processed as reported in the Section 2.1.

The dose maps measured by the Gafchromic films were compared with the corresponding dose distributions calculated by the TPS in