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Technical note

Experimental assessment of proton dose calculation accuracy in inhomogeneous media

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ABSTRACT

Purpose: Proton therapy with Pencil Beam Scanning (PBS) has the potential to improve radiotherapy treatments. Unfortunately, its promises are jeopardized by the sensitivity of the dose distributions to uncertainties, including dose calculation accuracy in inhomogeneous media. Monte Carlo dose engines (MC) are expected to handle heterogeneities better than analytical algorithms like the pencil-beam convolution algorithm (PBA). In this study, an experimental phantom has been devised to maximize the effect of heterogeneities and to quantify the capability of several dose engines (MC and PBA) to handle these.

Methods: An inhomogeneous phantom made of water surrounding a long insert of bone tissue substitute ($1 \times 10 \times 10$ cm^3) was irradiated with a mono-energetic PBS field (10×10 cm^2). A 2D ion chamber array (MatriXX, IBA Dosimetry GmbH) lied right behind the bone. The beam energy was such that the expected range of the protons exceeded the detector position in water and did not attain it in bone. The measurement was compared to the following engines: Geant4.9.5, PENH, MCsquare, as well as the MC and PBA algorithms of RayStation (RaySearch Laboratories AB).

Results: For a γ-index criteria of 2%/2 mm, the passing rates are 93.8% for Geant4.9.5, 97.4% for PENH, 93.4% for MCsquare, 95.9% for RayStation MC, and 44.7% for PBA. The differences in γ-index passing rates between MC and RayStation PBA calculations can exceed 50%.

Conclusion: The performance of dose calculation algorithms in highly inhomogeneous media was evaluated in a dedicated experiment. MC dose engines performed overall satisfactorily while large deviations were observed with PBA as expected.

1. Introduction

Among proton therapy (PT) delivery techniques, Pencil Beam Scanning (PBS) delivery enables variable intensity modulation (IMPT) and has showed a potential to improve radiotherapy treatments. However, several uncertainties impacting the proton range inside the patient jeopardize this potential of PBS. In complex inhomogeneous media, dose calculation (i.e. treatment planning) may contribute significantly to these uncertainties [1,2]. Monte Carlo (MC) based algorithms are considered in the literature as the gold standard for dose calculation since they are directly sampling models of the physical laws underlying the interactions of particles with matter. In the last decade, several MC dose engines with extremely fast dose calculation times have been described in the literature, which opens the path towards implementing MC in clinical practice. Nevertheless, most clinical solutions still rely on dose engines with analytical transport methods, in order to achieve fast dose computations. These analytical dose calculation algorithms have inherent difficulties to handle density interfaces correctly, especially those parallel to the beam. Even if analytical algorithms

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have been improved to take into account the effect of density heterogeneities [3,4], several publications showed significant differences between TPS calculations using pencil beam (PBA) or ray-tracing algorithms and MC simulations in clinical case studies [5–9]. For instance, Paganetti et al. [1] showed the prospective advantage of using MC in the presence of lateral heterogeneities. MC-based algorithms are supposedly more accurate than analytical simulations in complex cases [5,10]. However, MC dose engines differ in their implementation, especially after the last half-decade that has seen the advent of extremely fast MC codes, with physics models implementation that are optimized and simplified to speed up the simulation while preserving reasonable accuracy. Thus, the added value of MC codes and their resilience to highly inhomogeneous anatomies should be assessed and quantified experimentally before clinical implementation.

This work aims to evaluate one analytical and several MC dose engines in an experimental phantom that has been specifically designed to magnify the effect of lateral heterogeneities and yet yield interpretable results. The long-term perspective of this work is to establish a reference experimental setup for convenient testing the performance of dose calculation algorithms in highly inhomogeneous media.

2. Methods

2.1. Experimental setup

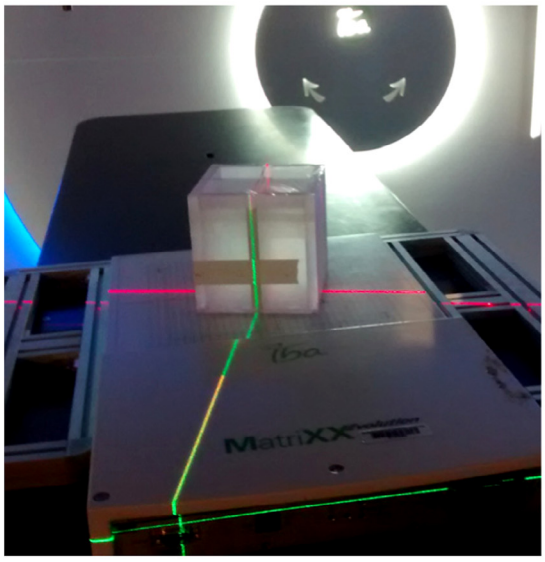
The phantom consists of a sliver of bone tissue substitute (SB3 from Gammex), inserted in a water tank as is shown in Fig. 1. The size of the sliver bone is $1 \times 10 \times 10$ cm^3. The tank is filled with liquid water. The volume between the bone sliver and the detector consists of PMMA, which is also the material of the bottom of the tank.

The mass density of the bone sliver is 1.82 g.cm^{-3}. The atomic composition of the bone equivalent material has been disclosed by the manufacturer (3.41% H, 31.41% C, 1.84% N, 36.5% O, 0.04% Cl, 26.81% Ca) [11]. The solid water plates are composed of PMMA. The density of PMMA plates is 1.15 g.cm^3.

The beam was delivered by a universal nozzle (Ion Beam Applications s.a, Louvain-la-neuve, Belgium) installed in MGH (Massachusetts General Hospital, Boston, USA). A universal nozzle can deliver multiple types of treatment: passive scattering, uniform scanning, and pencil beam scanning (PBS). The PBS beam direction is parallel to the bone sliver coming from the top of the water-bone box. The proton field size is 10×10 cm^2 and homogeneous in intensity. The nominal proton range is 18 g.cm^{-2} or 162 MeV.

The material interface is parallel to the proton beam. The region of interest for the study is the region around and right below the bone sliver position. Potential proton trajectories with a single scattering are schematically illustrated in Fig. 1(ii). The phantom and detector arrangement have been designed to maximize the effects of multiple scattering with protons. The incidences close to the interface are expected to have different ranges depending on their multiple scattering "history" along the interface, with multiple changes of density along their total path.

The detector is a 2D ion chamber array detector MattriX (IBA Dosimetry GmbH). The detector is placed underneath the phantom and the PMMA layer. The experimental setup is placed on the patient couch and the gantry is positioned at 0°. The detector is calibrated to measure dose-to-water. The pitch of the MattriX ion chambers is 7.62 mm. In order to improve spatial resolution of the acquired data, the phantom is rotated by 15 degrees around the beam axis. By this we take advantage of the phantom symmetry and field homogeneity. Spatial resolution is then reduced to less than 1 mm by calculating the distance of several data points to the bone sliver axis.



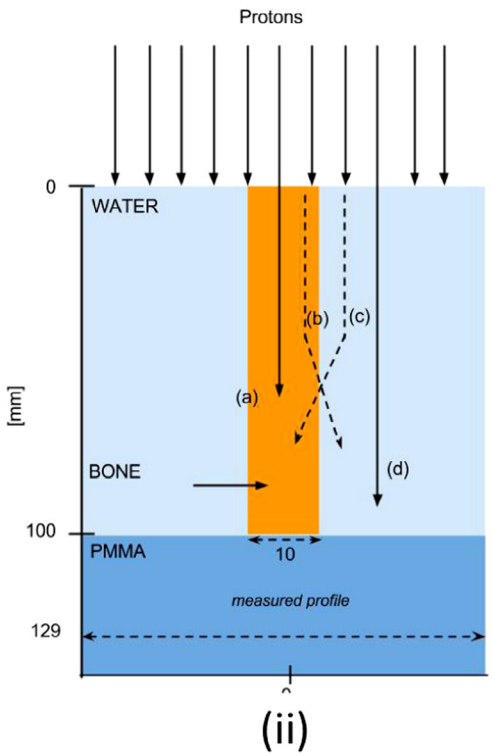


Fig. 1. (i) Experimental setup including the bone-water tank and the detector placed on the patient couch. (ii) There are mainly four typical trajectories across these interfaces. The first trajectory (a) is the one where protons go through all bone sliver. The box dimension and the nominal beam energy is such that such protons should stop before the end of the sliver. The trajectory (b) and (c) correspond to protons scattering from bone to water and vice versa as they penetrate inside the phantom. The last trajectory (d) corresponds to protons depositing their energy mainly in water and not influenced by the presence of the bone sliver.