In-vivo dosimetry and range verification: prospects for using gadolinium-based contrast agents to track the treatment plan delivery

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Introduction

Uncertainties in the proton range, patient geometry or positioning, threaten the precise and secure delivery of the treatment plans (TP) in proton radiotherapy [1]. In vivo range and dose distribution determination are crucial for TP adaptation and mitigating uncertainties.
Gadolinium-based contrast agents (GBCAs), commonly used in MRI, exhibit prolonged tumour retention. Upon proton irradiation, secondary photons are created, which are detectable outside the patient body [2].
This study explores the usage of Gd as a surrogate for non-invasive in vivo dosimetry as well to measure the incident protons residual range, recording real-time secondary photons emitted upon proton-Gd interaction.

Materials & Methods

Monte Carlo simulations were performed using Topas 3.9 or Geant4 11.1.1. A GBCA-filled volume was placed within a water phantom. The target was irradiated with single spot beams of various energies or using a MatRad-generated scanning TP (4 Gy). Several scenarios were simulated, where the target was displaced inside the water phantom, while the X-ray and prompt-gamma signal from the proton-Gd interaction were assessed.
Parameters including Gd spectral response, spatial dose distribution, integral dose to the target, incident primary proton energy and LET were scored for each position.

Results

The spectral signature of Gd exhibits a dominant characteristic x-ray peak around 43 keV. The study demonstrated the ability to track the deposited dose at the target volume for each TP scanning point, figure 1a. Displacements from the planned geometry were also detected by observing changes in the Gd signal at each TP point and after delivering the full TP, figure 1b. Therefore, it showed to be possible to follow the delivery of a pencil beam scanning proton TP, which opens possibilities to intra- and inter- fraction adaption of TPs.

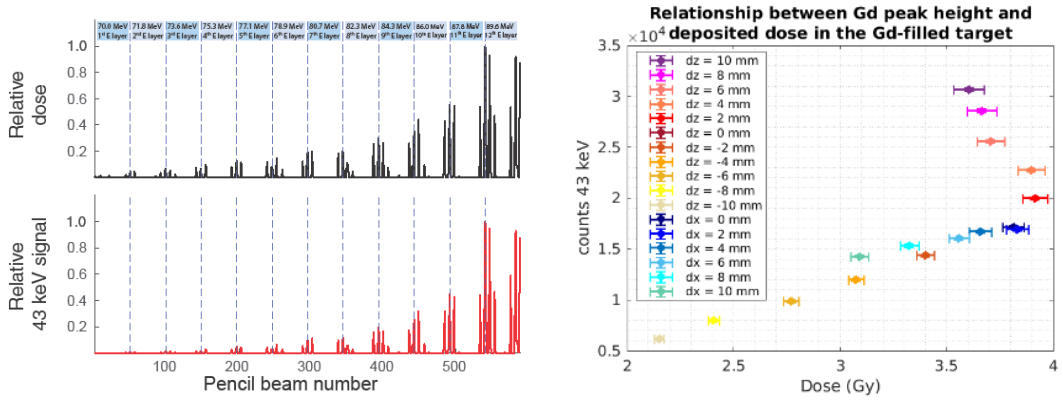

Figure 1. a) Relative dose delivered to the Gd-filled tumor by each of the pencil beams in the TP (top) and the correspondent secondary 43 keV characteristic Gd x-ray signal emitted (bottom), allowing TP tracking; b) Relationship between integral dose and total Gd signal for different scenarios (transversal and depth displacements).

Moreover, particle induced X-ray emission (PIXE) emerged as the main contributor to such peak. The cross section of PIXE significantly depends on the incident proton energy. Thus, the detectable Gd characteristic x-ray signal can be correlated with the primary proton energy reaching the tumour, this is with the residual range of the arriving protons, figure 2, enabling range prediction.

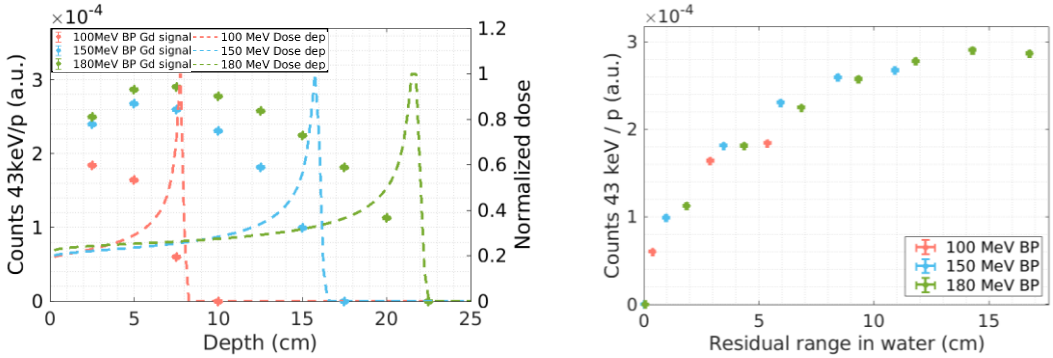

Figure 2. a) 43 keV signal after irradiation with 100, 150 and 180 MeV single proton pencil beams of a small volume of Gd, placed at different positions along the BP. b) Correlation between the 43 keV signal and the residual range of the arriving protons at the target volume.

Conclusions: This study researches the opportunities of using Gd as a surrogate for in vivo dosimetry and residual range determination, which provides insights into treatment plan delivery.

References

[1] Paganetti, H. Physics in Medicine & Biology, 2012, 57.11: R99.

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