Electron density resolution determination and systematic uncertainties in proton computed tomography (pCT)

George Dedes, Simon Rit, Denis Dauvergne, Marieke De Rydt, Nicolas Freud, Jochen Krimmer, Jean-Michel Létang, Cedric Ray, Etienne Testa

***Abstract*–The use of protons in radiotherapy offers a very precise and effective tool for malignant tumor treatment. In order to fully exploit the benefits of proton therapy, a precise determination of the proton range inside the patient is needed. Currently, this information is provided by conventional X-ray CT. In our work, we explore the theoretical limits of proton CT by means of Monte Carlo simulations. We focus on the accuracy in determining the electron density of different clinical relevant materials and the systematic uncertainties that influence the measurement with an ideal cone beam proton CT scanner.**

Radiotherapy with proton beams offers significant advantages over conventional X-ray radiotherapy. The main distinctive characteristic of proton beam is the depth dose curve. A very low entrance dose combined with a sharp rise of dose deposition near the end of the proton range (Bragg peak) makes possible to deliver the prescribed dose in a high conformal way and with millimetric accuracy. This results to significant sparing of healthy tissues and organs at risk around the tumor.

In order to fully exploit the benefits of proton therapy, a precise determination of the proton range inside the patient is needed. Currently, the information used is provided by conventional X-ray CT. Therefore, treatment planning relies on the conversion of photon attenuation to stopping power. This conversion is done by using a calibration curve which relates the CT measured Hounsfield units to stopping power. The above described process results in systematic uncertainties which limit the efficiency of proton therapy. Those uncertainties have been estimated [1] to be about ±1.1% in the case of soft tissue and ±1.8% in the case of bone, which translates into a range precision of 1-3 mm in typical treatment situations.

Alternatively, protons can also be used for imaging purposes [2] [3]. In that case, a proton beam is used, whose energy is higher than that during treatment, so that protons can penetrate the patient and deposit only a small fraction of their energy in the body. From that process one obtains directly a 3D stopping power map of the area under treatment. The actual derived quantity in proton CT is the electronic density which can be used for treatment planning, namely to calculate proton stopping power at the treatment energy. Therefore, electron density determination is one of the major performance parameters for proton CT regarding its utilization in treatment planning.

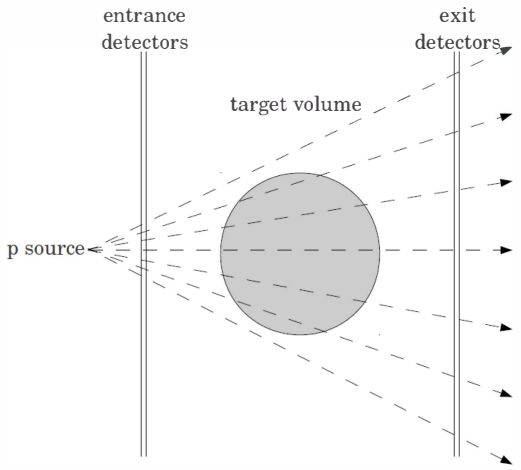

Fig.1: Schematic view of the ideal pCT scanner used in this study.

In our work, we focus on the accuracy of the measurement of electron density by means of Monte Carlo simulations. Calculations have been performed with the GATE version 6.2 platform based on GEANT4 version 9.5. As the scope of this study is to assess the theoretical limits of proton CT, an ideal scanner has been used.

The simulated device consists of two perfect detector planes. One before the entrance of the target and a second identical plane positioned after the exit from the target, both registering the energy, the direction and the position of the impinging protons. A simple cone beam geometry was considered with proton energy of 250 MeV. For the reconstruction of the images and the calculation of electron density, we use the distance-driven binning filtered backprojection (FBP) algorithm developed at the CREATIS lab [4]. In this algorithm, curved most likely paths (MLP) are assumed for the protons, which is an novel approach for FBP algorithms.

For the estimation of electron density accuracy we simulate cylindrical homogeneous targets of of various materials and

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G. Dedes, D. Dauvergne, J. Krimmer, C. Ray and E. Testa are with IPNL, Université de Lyon, F-69003 Lyon, France; Université Lyon 1 and CNRS/IN2P3, UMR 5822 F-69622 Villeurbanne, France, (e-mail: g.dedes@ipnl.in2p3)

M. De Rydt is with the Instituut voor Kern- en Stralingsfysica, K.U.Leuven, Celestijnenlaan 200D, B-3001 Leuven

S. Rit, N. Freud. J. M. Letang are with CREATIS, Université de Lyon, F-69622 Lyon, France; Université Lyon 1 and CNRS UMR 5220; INSERM U1044; INSA-Lyon; Centre Léon Bérard, France

sizes. The material of the target varies from soft tissue equivalents like lung (d=0.26 g/cm^3), adipose tissue (d=0.92 g/cm^3), water (d=1 g/cm^3), muscle (d=1.05 g/cm^3), to rib bone (d=1.92 g/cm^3). The electron density of a central region of interest (ROI) inside the target is calculated. We compare the obtained values with the theoretical ones for each material and express the electron density resolution as the one standard deviation of the calculated distributions.

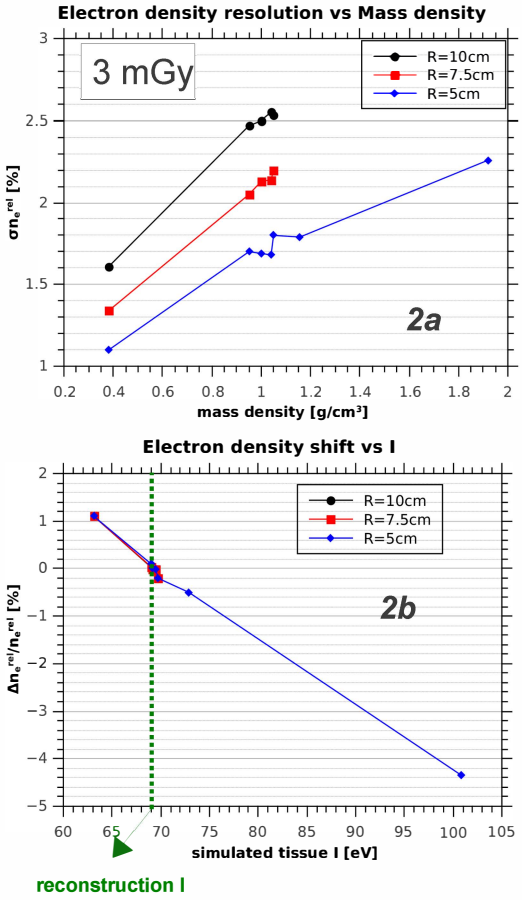

Fig. 2: Influence of different mean excitation energy values used for the same material (water). The three values are I=68.9eV and 80.8eV (extreme values found in literature for water) and 102.82eV for rib bone. 2a *the percentage difference in proton energy straggling versus target depth,* 2b *the percentage mean energy difference versus target depth.*

Furthermore we determine the systematic errors in the electron density derivations. The main contribution studied comes from the common assumption of a space independent mean excitation energy *I* for the whole object and for all materials. Usually, the value of *I* used is that of water. This value can deviate by as much as 30% from the one corresponding to bone.

In Fig.2a, the performance in terms of electron density resolution is presented for a dose of 3mGy and for different tissues and homogeneous phantom sizes. An electron density resolution of 1% is achieved with about 20 mGy for a perfect scanner.

As shown in Fig.2b , the assumption of a mean excitation energy different than the true one, can lead to deviations in electron density. We present a study of this bias for different tissues, for both homogeneous and inhomogeneous targets and finally we quantify the dependence of this bias on the location in the target and on the tissue type.

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