Spectral CT based elemental composition assignment to increase the accuracy of Monte Carlo simulation in proton beam therapy

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INTRODUCTION

Monte Carlo (MC) simulation of radiation transport is considered to be the most accurate method for dose computation in radiation therapy. Computerized tomography (CT) data are used to define patient geometry for MC simulation. Schneider's algorithm [1] is currently utilized for converting CT numbers to mass density and elemental weights. The algorithm defines 24 intervals of CT numbers from -1000 to 1600. A large number of tissue elemental compositions belong to one interval. Thus, tissues with different radiobiological properties or belonging to different organs or structures are often represented with the same elemental compositions.

PURPOSE

The purpose of this work is to improve elemental composition assignment with better tissue segmentation in Monte Carlo transport schemes for proton therapy by utilizing the pixel-by-pixel electron density (ED) and effective atomic number (Zeff) generated by spectral CT. We select brain patients for investigation of utilizing information acquired with the spectral CT in improving MC simulation.

METHOD

Three-dimensional ED and Zeff maps were retrospectively reconstructed from patient brain scans acquired on a clinical detector-based spectral CT system.

An algorithm for segmenting white matter and gray matter in the brain were formulated based on Zeff-ED pairs. The Schneider's algorithm represents white matter and gray matter with the same elemental composition because both fall in the same CT numbers interval of 18-80 HU (Figure1). The Zeff was calculated as

$$Z_{eff} = \sqrt[n_z]{\sum_i f_i Z_i^{n_z}} \qquad \text{(Eq.1)}$$

where f_i is the fraction of the total number of electrons associated with each element, n_z =2.94 [2]

We compared T1 weighted MR images with the spectral CT generated Zeff and ED.

The beam axis was defined in the treatment plans, and the proton beam passage for both segmentation algorithms was simulated with FLUKA MC code. The single spot was simulated representing the lower and higher energy in a spread-out Bragg peak (SOBP). The geometry along the beam path was represented as layers of different materials (Figure 2). The thicknesses of the layers were determined from T1 weighted MR images.

Two material composition models were used for calculations. One is the material composition from Schneider's algorithm and other for the elemental composition of the white and gray matters, The depth dose difference along the beam axis was analyzed.

RESULTS

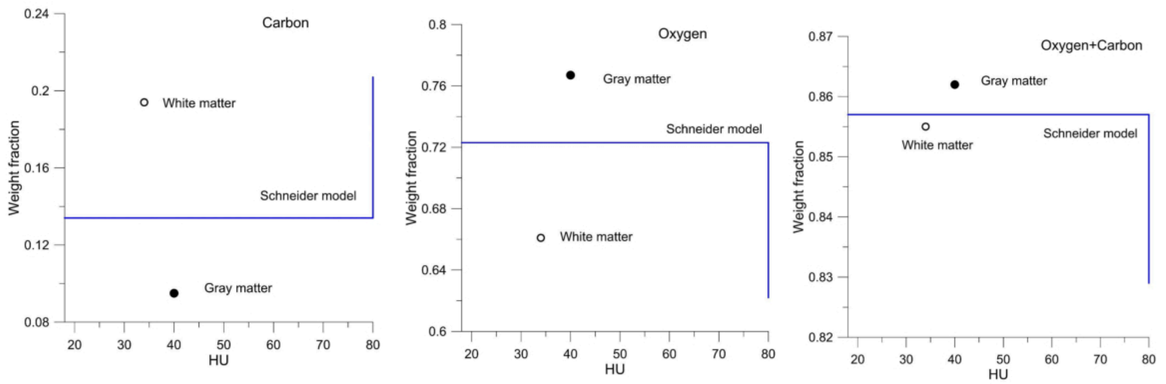


Figure 1. Elemental compositions of white and gray matters are assigned identically by the Schneider's method (PMB 2000) because their CT numbers fall within the single interval of 18 to 80.

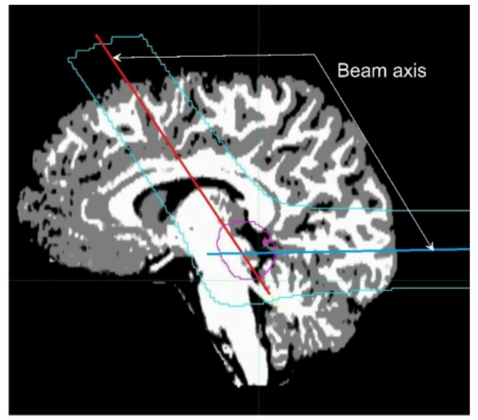


Figure 2. The beam axis and definition of the geometry for gray matter and white matter representation for the proton beam simulation.

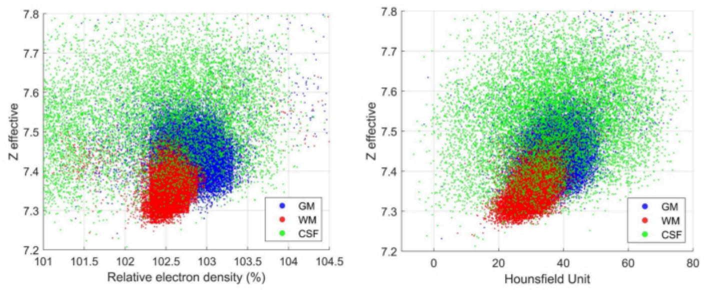


Figure 4. Scatter plots of Zeff-ED and Zeff-HU for the brain below demonstrate well-separated cluster centers of white matter (red cluster) and gray matter (blue cluster).

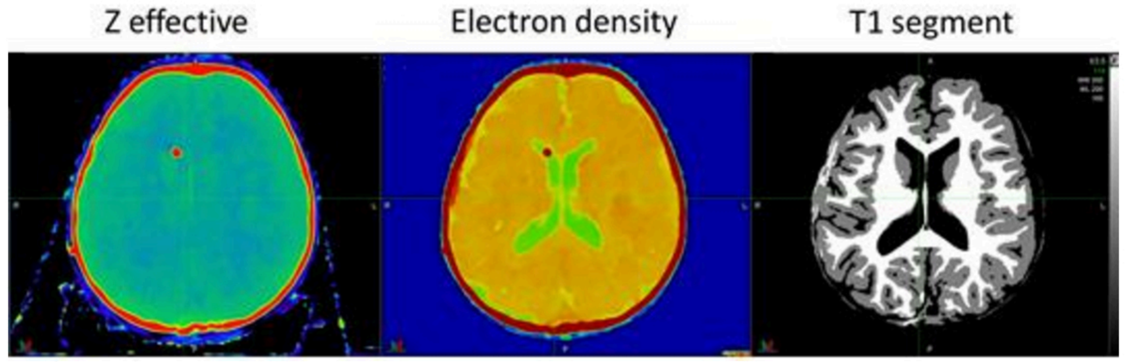
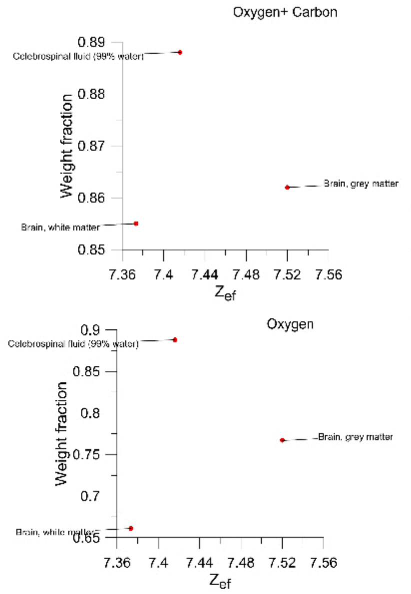


Figure 5. Effective atomic number (left), electron density (middle), and T1 weighted MRI (right) demonstrate the feasibility of separating white matter and gray matter based on spectral CT images.



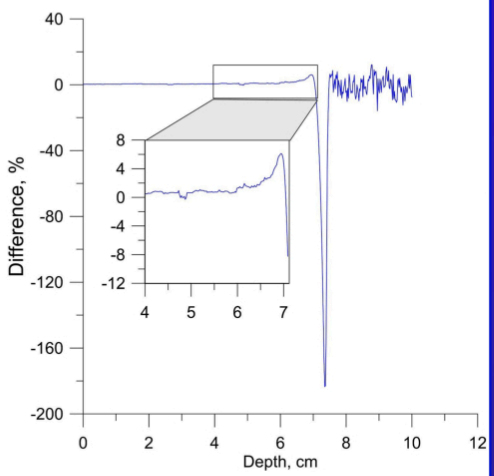


Figure 3. The calculated Zeff values for white and gray matters using Eq.1 shows possibility of the tissue segmentation using Zeff. ED method from the MC simulation.

Figure 6. The dose difference between the Schneider's method and the Zeff-ED method from the MC simulation.

Estimated Zeff with the Eq.1 using the reference elemental composition is 7.37 for the white matter and 7.52 for the gray matters (Figure 3). The estimated Zeff for the elemental composition of 18-80 CT numbers interval in the Schneider's algorithm is 7.40. The value of Zeff equal to 7.445 can be used as the threshold to assign the elemental composition for gray or white matters.

Scatter plots of Zeff vs. ED and Zeff vs. CT numbers (HU) show different distributions of white and gray matters with well-separated cluster centers (Figure 4). Thus, the Zeff map can help in the segmentation of the tissue elemental composition.

Comparison of the Zef, ED and T1 weighted MRI maps (Figure 5) demonstrate the feasibility of separating white matter and gray matter based on spectral CT images.

Simulations of a spot scanning beam for Schneider's algorithm and Zeff-ED based segmentation shows a difference in the depth dose distributions and range (Figure 6).

The Schneider algorithm underestimated the energy loss that may result in a larger proton range and lower dose at the spot position.

DISCUSSION

The white and gray matters have different elemental compositions [3] and show a significantly different response to radiation [4, 5].

The error in the transport calculations due to lack of the accounting the elemental compositions for white and gray matters may be from 0.2 to 1 mm. This error is within the agreement with the reported data.

The accuracy in proton beam treatment calculations can be increased if Monte Carlo algorithms can adopt the Zeff map as a trigger for the elemental composition assignment. The Schneider algorithm may need an amendment to assign additional sets of the elemental compositions in the interval selected based on CT numbers using the Zeff as a trigger for different parts of the human body.

CONCLUSIONS

The Zeff-ED tissue segmentation for elemental composition assignment may increase the accuracy of the MC simulation in proton therapy.

Gray matter and white matter tissues can be separated on the Zeff-ED and Zeff-HU space.

The impact of more accurate tissue segmentation in MC simulation will be important for treating tumors close to critical organs and for radiobiological response simulation with MC.

ACKNOWLEDGEMENTS

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REFERENCES

1. **Schneider W *et al.*** Correlation between CT numbers and tissue parameters needed for Monte Carlo simulations of clinical dose distributions. *Phys Med Biol.* 2000;45(2):459-478.
2. **Hua C-H *et al*.** Accuracy of electron density, effective atomic number, and iodine concentration determination with a dual-layer dual-energy computed tomography system. *Medical Physics.* 2018;45(6):2486-2497.
3. **Steen RG *et al.*** Effect of ionizing radiation on the human brain: White matter and gray matter T1 in pediatric brain tumor patients treated with conformal radiation therapy. *International Journal of Radiation Oncology Biology Physics.* 2001;49(1):79-91.
4 **Steen RG *et al*.** Effect of therapeutic ionizing radiation on the human brain. *Annals of Neurology.* 2001;50(6):787-795.
5. **Woodard HQ, White DR**. The composition of body tissues. *British Journal of Radiology.* 1986;59(708):1209-1219.

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