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Impact of the material composition on proton range variation – A Monte Carlo study

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HIGHLIGHTS

- Using Geant4 to study the impacts of the material composition on proton range.
- Bragg curves simulation of different materials for 250 MeV proton beam.
- Test material: adipose, heart, brain, cartilage, cortical bone, air, and water.
- Significant range deviation in cortical bone and air.
- Electron density providing better range scaling.

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ABSTRACT

In this study, we used the Geant4 toolkit to demonstrate the impacts of the material composition of tissues on proton range variation. Bragg curves of different materials subjected to a 250 MeV mono-energy proton beam were simulated and compared. These simulated materials included adipose, heart, brain, cartilage, cortical bone and water. The results showed that there was significant proton range deviation between Bragg curves, especially for cortical bone. The R_{50} values for a 250 MeV proton beam were approximately 39.55 cm, 35.52 cm, 37.00 cm, 36.51 cm, 36.72 cm, 22.53 cm, and 38.52 cm in the phantoms that were composed completely of adipose, cartilage, tissue, heart, brain, cortical bone, and water, respectively. Mass density and electron density were used to scale the proton range for each material; electron density provided better range scaling. In addition, a similar comparison was performed by artificially setting all material density to 1.0 g/cm^3 to evaluate the range deviation due to chemical components alone. Tissue heterogeneity effects due to density variation were more significant, and less significant for chemical composition variation unless the Z/A was very different.

1. Introduction

Proton therapy has become an excellent treatment for tumours, owing to its excellent dose characteristic, its Bragg peak, which occurs almost before the range where protons come to rest. Compared to photon, this proton range brings one more degree of freedom for concentrating doses on tumours while minimizing adverse effects on the surrounding healthy tissue. Consequently, tissue heterogeneity is more of an issue in proton therapy because its resultant range perturbation may reduce the accuracy of proton delivery. The impacts of tissue heterogeneity to range variation can be divided into two influencing factors: mass density and chemical composition of tissues/organs.

Treatment planning system (TPS) usually corrects tissue heterogeneity as water in different densities. The Monte Carlo (MC) method, however, models heterogeneity according to its mass density and chemical composition. The dose deviation caused by these different approaches has long been studied for photon therapy. Siebers et al. (2000), Dogan et al. (2006) and the AAPM TG-105 (Chetty et al., 2007) reported that dose deviation in high-density tissue (i.e. cortical bone) is significant, and conversion

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factors derived from the Bragg–Gray (BG) cavity theory should be applied to reduce this deviation. In Siebers' studies, the mass stopping power ratio caused about 1% dose deviation for soft tissue and 10% for cortical bone. Dogan et al. also mentioned that the clinical outcome of the isodose and the DVH resulted in errors of 5.8% for head-and-neck and 8.0% for prostate IMRT cases. Such a dose deviation may result in a 10–20% change in tumour control probability (TCP) or up to a 20–30% change in normal tissue complication probabilities (NCTP) if the prescribed dose falls along the steepest region of the dose–effect curves (Chetty et al., 2007).

The impacts of tissue heterogeneity on proton dosimetry have been less studied. Jiang et al. (2007) studied the effects of Hounsfield number conversion on CT-based proton Monte Carlo dose calculations. Instead of treating human tissues as water of various densities in analytical algorithms, their study allowed human tissues to be characterized by elemental composition and mass density, and hence allowed for the accurate consideration of all relevant electromagnetic and nuclear interactions. Paganetti (2009) developed a formula to convert dose to medium into dose to water for proton, based on the relative stopping power, and took into consideration energy transferred via nuclear interactions.

The presented study utilized Monte Carlo simulations on seven slab-based phantoms entirely made of different tissue materials to demonstrate the range fluctuation caused by mass density and chemical composition.

2. Materials and methods

To investigate the impact of tissue materials on proton range variation, Bragg curves, i.e. the plot of deposited energy along the track of a charged particle, in eight slab-based phantoms were simulated. In this study, a 250 MeV mono-energy proton pencil beam was simulated using Geant4 (GEometry ANd Tracking Ver. 4), a toolkit for MC simulation, which is useful in applications such as high energy, nuclear and accelerator physics, as well as studies in medical and space science (Agostinelli et al., 2003). The proton pencil beam was shot perpendicularly into several slab-based phantoms that were entirely made up of adipose, heart, brain, cartilage, cortical bone, soft tissue, and water. The densities and chemical composition of these materials are listed in Table 1. The slab-based phantoms were constructed by using fifty parallel $10 \times 10 \times 1\ \text{cm}^3$ slabs.

Before Bragg curves were simulated, an inter-comparison of proton dose distribution in water phantoms using MCNPX, GEANT4 and FLUKA was performed to ensure the accuracy of GEANT4 setup (Lee et al., 2014). Differences of simulated $R_{50\%}$ (range for proton dose down to 50% of maximum) values among the three codes were less than 1 mm.

To emphasize the range deviation owing to chemical composition, three approaches were implemented to negate the impact from mass density: (1) converting the depth into density depth of different Bragg curves by using the mass density; (2) converting the depth into water equivalent depth of different Bragg curves by using the electron density; and (3) performing additional Bragg curve simulations by artificially setting all material densities to $1.0\ \text{g}/\text{cm}^3$. As the mass densities of different tissues were unified, the range deviation owing to chemical composition was emphasized.

Finally, we also shot a 150 MeV proton beam into slab-based phantom, which was interlaced with water and cortical bone slabs with a thickness of 2 mm, to demonstrate the range shift owing to different materials. For the simulation of this specially designed phantom, its density was also artificially set to $1.0\ \text{g}/\text{cm}^3$.

3. Results and discussion

Bragg curves from different materials against a 250 MeV mono-energy proton beam were plotted and compared, as shown in Fig. 1. In this study, we normalized energy deposition at all depths to the depth of 10 cm, where there was almost no dose gradient and build-up. The comparison showed significant deviation among the proton ranges from different materials, especially for cortical bone. The $R_{50\%}$ was 39.55 cm, 35.52 cm, 37.00 cm, 36.51 cm, 36.72 cm, 22.53 cm, and 38.52 cm for adipose, cartilage, soft tissue, heart, brain, cortical bone, and water, respectively. The Bragg curve of cortical bone deviated most since its density was much larger than other tissue materials. It would be interesting to know whether it was the density or the chemical composition that predominantly affected this range deviation.

The relationship between the proton range and density were analysed using the linear regression method:

$$R_{50\%} = -27.917\rho + 66.085 \quad (1)$$

where ρ is the mass density of different tissue materials, and the coefficient of determination was $R^2 = 0.9759$, which indicated that there was a strong relationship between mass density and proton range. Therefore, we could re-plot the Bragg curves (Fig. 1) using the density depth (Fig. 2) which was equal to the depth multiplied by density. After the density scaling, most Bragg curves, except for cortical bone, showed good agreement with each other and the standard deviation of $R_{50\%}$ was only 0.44 cm (about 1% of the range). Mass density may be a good scaling factor for range estimation for proton therapy.

The relationship between the proton range and electron density were also analysed using the formula:

$$R_{50\%} = -31.662\rho_{e,rel} + 69.744 \quad (2)$$

where $\rho_{e,rel}$ is the electron density of tissues relative to water and $R^2 = 0.9731$. We could also re-plot Fig. 1 using the water equivalent depth (Fig. 3) that was equal to the depth multiplied by electron density of tissues relative to water. After the electron density scaling, Bragg curves showed an even better agreement

Table 1
The mass density and chemical composition (weight percentage) of different tissue materials from ICRU 44 (Bethesda et al., 1989), ICRU 33 (Bethesda et al., 1980) and ICRP 23 (Snyder et al., 1974).

Tissue	Density (g cm^{-3})	Z/A	H (%)	C (%)	N (%)	O (%)	Others (%)
Lung (ICRU 44)	0.28 (ICRU 44)	0.550	10.3	10.5	3.1	74.9	Na 0.2, S 0.3, Cl 0.3, P 0.2, K 0.2
Adipose (ICRU 44)	0.95 (ICRU 44)	0.556	11.4	59.8	0.7	27.8	Na 0.1, S 0.1, Cl 0.1
Water	1.00	0.555	11.2			88.8	
Soft tissue (ICRU 33)	1.04 (ICRP 23)	0.550	10.1	11.1	2.6	76.2	
Brain (ICRU 44)	1.04 (ICRU 44)	0.552	10.7	14.5	2.2	71.2	Na 0.2, S 0.2, Cl 0.3, P 0.4, K 0.3
Heart (ICRU 44)	1.06 (ICRU 44)	0.550	10.3	12.1	3.2	73.4	Na 0.1, S 0.2, Cl 0.3, P 0.1, K 0.2, Fe 0.1
Cartilage (ICRU 44)	1.10 (ICRU 44)	0.547	9.6	9.9	2.2	74.4	Na 0.5, S 0.9, Cl 0.3, P 2.2
Cortical bone (ICRU 44)	1.92 (ICRU 44)	0.515	3.4	15.5	4.2	43.5	Na 0.1, S 0.3, P 10.3, Ca 22.5, Mg 0.2