Comparison of stopping power estimators from dual-energy computed tomography for proton therapy

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Purpose or Objective: Proton range in patients is determined from the stopping power ratio (SPR) of tissues relative to water along the beam path. SPR map can be derived from dual-energy computed tomography (DECT) and the Bethe-Bloch equation. In this study, we propose and compare the accuracy and the precision of several procedures to estimate the SPR from DECT.

Material and Methods: Image-based method of [1] and projection-based material decomposition (BMD) method of [2] were investigated. 2 variants for BMD were considered: water/compact bone basis (W/CB) and photoelectric/Compton basis (Ph/Co) with exponent optimization for the given DE spectra. BMD assumes that linear attenuation coefficient at any energy can be obtained by a linear and energy-independent combination of these basis functions. Electron density $\rho_e$ and effective atomic number Zeff are common DECT outputs. For each decomposition method, 4 empirical relationships to convert DE outputs to SPR were evaluated which were all calibrated with materials used by [3] for the stoichiometric calibration. The first approach [4] was a calibrated relation between the log of the mean excitation energy of tissues $\ln$ Im and Zeff ($Z_{\text{eff}}, \ln \text{Im}$). The second approach consisted in reconstructing the electronic cross section at 100 keV $\sigma_e$ from the BMD results. To avoid intermediate variable Zeff, a novel calibrated relation between $\sigma_e$ and Im values was proposed. The third approach involved a calibration curve between ($\rho_e$, SPR/$\rho_e$) and ($Z_{\text{eff}}, \ln \text{Im}$) was proposed. The third method involved a calibration curve between ($\rho_e$, 100, SPR/$\rho_e$) and ($Z_{\text{eff}}, \ln \text{Im}$) behaved in the same manner. Results show that the method proposed by [5] provides better accuracy and precision.

Results: Relative errors of SPRs of phantom inserts estimated using 4 empirical relationships for each decomposition method are shown in Table 1 as $\mu \pm \sigma$. A penalty was imposed to pixel values with Im, Zeff and $\rho_e$ values outside human range. Lung tissue inserts show maximum error. ($\rho_e$, SPR/$\rho_e$), approach is the least appropriate in terms of precision. ($\rho_e$, 100, SPR/$\rho_e$) curve was added to the projections.

Conclusions: Comparison of different calibration methods to convert DE data into SPR was carried out. A novel relationship between $\rho_e$ and Im was proposed and behaves similarly to ($Z_{\text{eff}}, \ln \text{Im}$) curve. Energy independent poly-line (pe,SPR/pe) curves present better accuracy and precision. DECT is a promising technique to determine the SPR of human tissues. Optimization of the acquisition parameters and the algorithm to extract the required patient information is mandatory.

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Purpose or Objective: Proton and ion therapy require accurate prediction of particle ranges in tissue. In current clinical practice, computed tomography (CT) images are voxel-wise converted to ion-stopping power ratio maps using direct heuristic relations. The general validity of these approaches is, however, limited due to the different physical regimes of photon and ion interaction. Using a more sophisticated method based on dual-energy CT (DECT), which provides access to the physical quantities influencing photon attenuation, Hünemohr et al. (2014) reported an improved ion-range prediction for homogeneous tissue surrogates. Here, we present a major modification of the latter method, enabling a proper treatment of heterogeneities and mixtures on several structural levels, which represent a crucial feature of the realistic clinical situation.

Material and Methods: We treat the stopping-power ratio as the product of the electron density relative to water and a correction factor that implicitly involves the logarithmic dependence on the mean excitation energy (I-value). The relative electron density, being an important parameter in both photon and ion energy loss, can be derived directly from DECT scans using a universal and robust method. The correction factor, however, has to be determined with an empirical method. For this purpose, we propose to use the information from CT images that is complementary to the relative electron density, i.e. the electronic photon absorption cross section relative to water. Using the attenuation sum rule and Bragg’s additivity rule, the relative cross sections and correction factors were calculated for single elements, tissue base materials like water, lipid, etc. and tabulated real tissues.

Results: For a therapeutic beam energy of 200 MeV/u, the correction factor varies between 1.15 and 0.70 for single elements with atomic numbers between 1 and 100. Building up compounds from a certain number of elements, a maximum spread of possible values for the correction factor can be quoted for a given relative cross section, due to the mathematical structure of the variable space. In practice, this could be used as an uncertainty estimate for a given calibration. The accessible variable space is drastically reduced by admitting only tissue base materials such as water, lipids and hydroxyapatite. The space is further reduced by admitting only mixtures of real tissue materials. For human tissue, the correction factor is thus limited overall to a small range around one (0.96 - 1.02).

Conclusion: With the definition of the correction factor in the stopping-power ratio prediction and its relation to the relative cross section, a mathematically rigorous treatment of tissue mixtures was made possible. Such mixtures influence CT imaging of patients e.g. in the form of volume averaging in a CT voxel. This thorough treatment of mixtures is thus essential for the clinical applicability of DECT-based ion-range prediction.

Conclusion: DRRs yielded comparable geometry between CT and synCT. Future work will involve an intensity normalization for synCT DRRs. Image registrations were within clinically acceptable ranges. Efforts are needed to combine geometric and dosimetric errors of the entire synCT pipeline; establishing QA workflows to quantify these uncertainties are necessary for MR-only treatment planning.

Material and Methods: MR images of the phantom were acquired on a 1.0T High-Field Open MR-Simulator (Philips Medical Systems, Cleveland, OH). Triple echo ultra-short echo time combined with mDixon (UTE/Dixon), T1-FFE, T2-TE, and FLAIR images MR images were acquired using an 8-channel head coil. Bone-enhanced images were generated via an optimal weighted combination of inverted UTE and water/fat maps automatically generated from mDixon. Images were then semi-automatically segmented using Gaussian mixture modeling before generating synCTs via a previously described region-specific, voxel-based, weighted summation method. SynCTs were validated by calculating the mean absolute error (MAE) between SynCT and CT-SIM. DRRs from CT-SIM and SynCT were generated of the phantom and geometric fidelity was assessed. On-board planar (MV/KV) and volumetric (CBCT) images were acquired of the phantom and rigid registration was compared between datasets across three linear accelerator platforms.

Results: The MAE of the synCT for the skull phantom (Fig 1E) was 131 HU. Embedded landmarks between the phantom CT-SIM DRRs and SynCT DRRs for both right lateral and anterior projections were <1 mm (1G). However, slight image intensity variations were observed across the DRRs in the synCT as compared to the CT-SIM. Bounding box analysis of the skull revealed that anterior-posterior DRRs were <1 mm different between synCT and CT-SIM while lateral DRRs had a slightly higher uncertainty in the anterior-posterior dimension (~2 mm). MV and KV planar image registrations were within 0.7 mm for all linear accelerators. CBCT/CT-SIM and CBCT/SynCT rigid registrations were <0.4 mm different.