Evaluation of Proton Computed Tomography Detected by Multiple-Layer Ionization Chamber and Strip Chambers through Monte Carlo Simulation with Human Head Phantoms

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HIGHLIGHTS

This study derived anthropomorphic phantoms from CT images, and utilized the phantoms with different levels of heterogeneity to evaluate the proton computed tomography (pCT) design. Not only has it demonstrated the ability of the pCT to image human anatomy with acceptable image quality and excellent accuracy, it has also provided guidance for pCT hardware and reconstruction optimization in the future.

INTRODUCTION

Current standard of practice to determine proton range is through calibration from Hounsfield unit of an X-ray computed tomography (xCT) scan. Nevertheless, the calibration brings in several extra sources of error, including the calibration error (up to 0.5% to 1.8% of the total proton beam range), xCT error (beam hardening, reconstruction artifacts, etc.), and patient positioning error (misalignment, motions, and anatomical changes).[1–5]

The uncertainty in translating photon attenuation to proton stopping power ratio (SPR) can be eliminated if SPR is measured by protons directly.

Our group reported the feasibility of a novel design of proton computed tomography (pCT) through Monte Carlo simulation with a cylinder phantom [ref]. In this study, we further evaluated the ability of the pCT to image real human anatomy by using a set of virtual human head phantoms.

RESULTS

The reconstructed SPR were compared with ground truth, which was derived from the CT images. Histogram of the percentage difference between reconstructed SPR and the ground truth, as well as the percentage difference of water equivalent path length (WEPL) at different projection angles and lateral displacements were displayed. For head phantom with one material, three materials and all materials, the averaged of percentage difference in ROI were 0.77%, 0.37%, and 0.11% respectively, and SNR in ROI were 28.91, 26.35, and 27.33 accordingly.

Reconstructed SPR of head phantom with one material of water, three materials of adipose, brain, and bone, and all original materials were displayed in Figure 1, in comparison with the corresponding ground truth or calibrated SPR showing on the left. Histogram of the percentage difference between reconstructed SPR and the ground truth or calibrated SPR, as well as the percentage difference of water equivalent path length (WEPL) at different projection angles and lateral displacements were displayed in Figure 2.

(a) (b) (c)

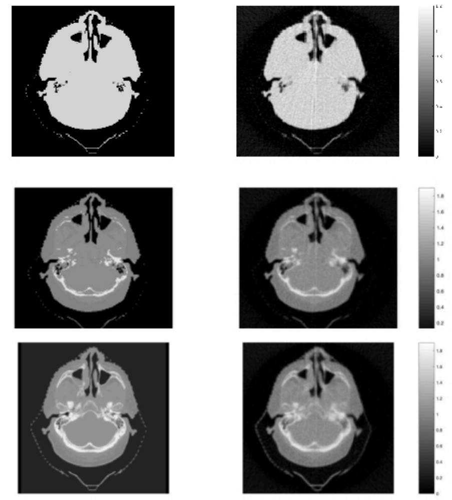

Figure 1. The reconstructed SPR for phantom with (a) one material of water, (b) three materials of adipose, brain, and bone, and (c) all original materials were displaced in comparison with the corresponding ground truth or calibrated SPR demonstrated on the left.

(a) (b) (c)

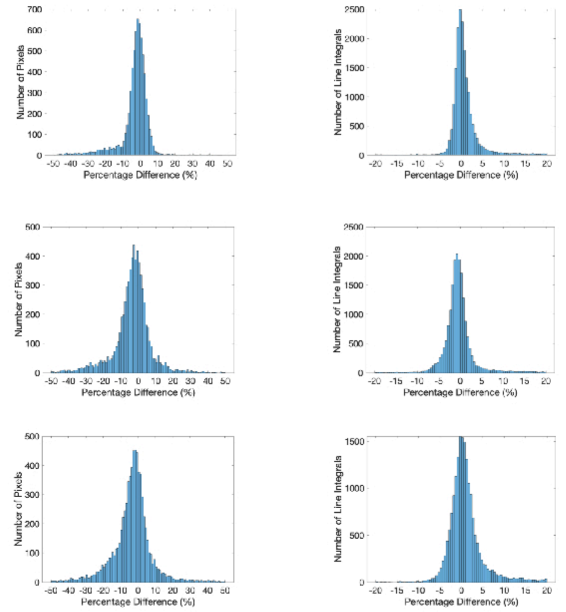

Figure 2. Histogram of the percentage difference between reconstructed SPR and the ground truth or overridden SPR(left column), and the percentage difference of WEPL (right column) for head phantom with (a) one material of water, (b) three materials of adipose, brain, and (c) all original materials.

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METHOD

The pCT detector was composed of a multiple-layer ionization chamber (MLIC) and two perpendicular strip chambers, so that the residual energy at different depth and the position of the exiting proton beam can be recorded. Proton stopping power ratio (SPR) was reconstructed through filtered-back projection. The human head phantoms were derived from a cohort of real patient CT scans acquired at our hospital. The Hounsfield Unit (HU) of CT images were converted to composition of materials based on Schneider's technique. The HUs used in the conversion were measured for 14 human tissue materials on the CT machine at our hospital. The head phantoms were overwritten to have one material of water, and three materials (adipose, brain, and bone) for quantitative analysis.

CONCLUSIONS

SPR reconstructed from the novel pCT design has acceptable image quality and excellent accuracy when imaging real human anatomy, indicating that the pCT design has great potential to be used in clinic for localization and plan adaption in proton therapy.

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