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Stopping-Power Ratio Accuracy for Proton Therapy: Photon-Counting Detector versus Energy-Integrating Detector CT

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ABSTRACT

Purpose: Stopping-power ratio (SPR) is used in proton therapy to calculate the radiation dose distributions. SPR depends on tissue composition and can be calculated using multi-energy CT. This study compares the accuracy of SPR calculated using energy-integrating detector CT (EID-CT) and photon-counting detector CT (PCD-CT).

Methods: A phantom (Gammex Multi-Energy CT Phantom, Sun Nuclear) containing nine tissue-like inserts was fitted to represent three different patient sizes (20, 40, and 50 cm lateral width). Scans were acquired on a dual-source dual-energy EID-CT (SOMATOM Force) at kV pairs of 80/150Sn, 90/150Sn, and 100/150Sn kV, and on a PCD-CT (NAEOTOM Alpha) at 120 and 140 kV. Images were reconstructed with a quantitative kernel (Qr40) and 2-mm slice thickness. SPR was calculated inside regions of interest within the inserts using prototype software provided by the manufacturer and compared to ground-truth values based on published literature and public databases assuming a 100 MeV proton energy. Mean absolute percent error (MAPE) was calculated across materials for different phantom sizes and kVs.

Results: Both EID-CT and PCD-CT demonstrated low SPR error relative to ground truth, however, PCD-CT consistently achieved lower error. Across all phantom sizes and materials, the MAPE was 1.12% for PCD-CT at both 120 and 140 kV, indicating no appreciable dependence on tube potential. For EID-CT, SPR accuracy showed a slight dependence on tube potential, with MAPE decreasing from 1.90% (80/Sn150 kV) and 1.78% (90/Sn150 kV) to 1.71% (100/Sn150 kV).

Conclusion: PCD-CT and EID-CT measurements of SPR both agree well with published ground truth, with PCD-CT slightly outperforming EID-CT. The MAPE averaged over all materials and kV setting for was 1.12% and 1.80% for PCD-CT and EID-CT, respectively, suggesting that both scanners yield accurate results for SPR.

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INTRODUCTION

Stopping-power ratio (SPR) is an important quantity used in proton therapy to calculate radiation dose distributions. It describes the amount by which protons or other particles are slowed by a material. SPR is defined by the Bethe equation [1]:

$$SPR = \rho_e \frac{K - ln(I)}{K - ln(I_w)}$$

Where ρ_e is the relative electron density of the tissue, K is a constant depending the kinetic energy of the protons, and I and I_w are the mean excitation energies of the tissue and water, respectively.

Accurate SPR calculations are crucial for correctly predicting the dose delivered to different anatomy during proton therapy. SPR can be calculated using multi-energy CT. Multiple technologies are clinically available for performing multi-energy CT. Most recently, photon-counting detector CT (PCD-CT) has been introduced and is being incorporated into therapy planning workflows within proton therapy facilities.

This study compares the accuracy of SPR calculated using conventional energy-integrating detector CT (EID-CT) and PCD-CT.

METHODS AND MATERIALS

A multi-energy CT Phantom (Gammex, Sun Nuclear) was configured to represent three different patient sizes of 20, 40, and 50 cm lateral width. Nine tissue-like inserts were fitted to represent liver, cortical bone, solid water, 30% $CaCO_3$, brain, breast, inner bone, blood, and adipose.

Scans were acquired on a dual-source dual-energy EID-CT (SOMATOM Force, Siemens Healthineers) at kV pairs of 80/150Sn, 90/150Sn, and 100/150Sn kV, and on a PCD-CT (NAEOTOM Alpha, Siemens Healthineers) at 120 and 140 kV.

Images were reconstructed with a quantitative kernel (Qr40) and 2-mm slice thickness. SPR was calculated inside regions of interest within the inserts using prototype software provided by the manufacturer and compared to ground-truth values based on published literature and public databases, assuming a 100 MeV proton energy.

Mean absolute percent error (MAPE) was calculated across materials for different phantom sizes and kVs.

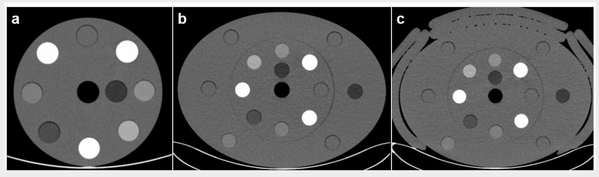

Figure 1. Phantoms used in this study. Images show 70 keV virtual monoenergetic reconstructions from PCD-CT of phantom sizes (a) Small (20 cm), (b) Medium (40 cm), and (c) Large (50 cm). W/L=400,40 HU. The phantom is rotated 90 deg. in the small configuration.

RESULTS

Both EID-CT and PCD-CT demonstrated low SPR error relative to ground truth, however, PCD-CT consistently achieved lower error.

Across all phantom sizes and materials, the MAPE was 1.12% for PCD-CT at both 120 and 140 kV, indicating no appreciable dependence on tube potential.

For EID-CT, SPR accuracy showed a slight dependence on tube potential, with MAPE decreasing from 1.90% (80/Sn150 kV) and 1.78% (90/Sn150 kV) to 1.71% (100/Sn150 kV).

Material	Alpha MAPE	Force MAPE
Liver	1.86	1.49
Cortical bone	0.88	4.56
Solid water	0.34	0.02
$CaCO_3$	0.33	2.07
Brain	1.55	1.02
Breast	1.49	1.55
Inner bone	0.06	1.39
Blood	1.76	2.12
Adipose	1.65	1.87

Table 1. Scanner MAPE averaged over kV and phantom size by material.

KEY RESULTS

Figure 1 shows sample images of differently sized phantoms from PCD-CT.

Figure 2 shows MAPE averaged across all materials for different phantom sizes and scanners/kVs, demonstrating that PCD-CT consistently achieved lower error, although the overall error was low for both PCD-CT and EID-CT (max MAPE <2.5%). A noticeable increase of MAPE was observed for large phantom on EID-CT, but not PCD-CT.

Figure 3 shows SPR across materials and imaging techniques, indicating accurate SPR for all materials in comparison with ground truth.

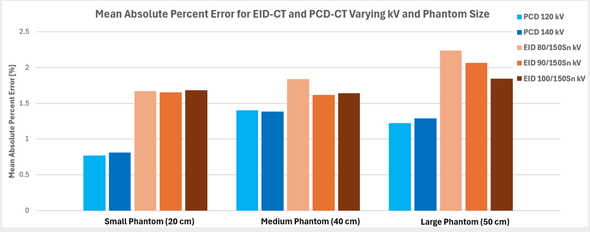

Figure 2. Mean Absolute Percent Error (MAPE) averaged over material type for different phantom sizes and scanners/kVs relative to ground truth values obtained from literature and public databases [2].

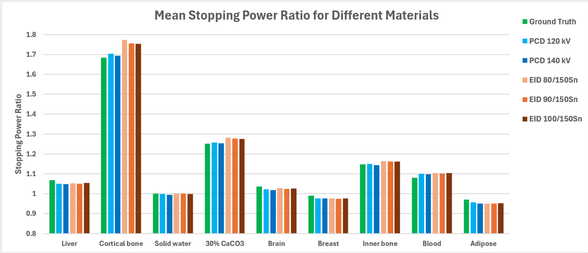

Figure 3. Stopping power ratio (SPR) for each material and scanner kV, averaged across the three phantom sizes.

DISCUSSION

PCD-CT and EID-CT both yielded accurate measurement of SPR.

Calculating the ground truth of SPR values depends sensitively on several factors. Phantom inserts can vary slightly in their true composition, leading to sightly different measurements between nominally identical setups. Therefore, some uncertainty exists since ground truth values were used from published literature.

Additionally, the determination of mean excitation energy I of the elements varies between sources and is still a subject of debate within the literature [3]. Because SPR depends so sensitively on this value, calculations can vary if an alternative approach is used.

Nonetheless, our findings show that both scanners tested in this work produce very small errors on average for different phantom sizes and kVs. The MAPE varied across material, with some being more accurate depending on the scanner.

Limitations of this study include that only one type of EID-CT was used for comparison and that insert composition for the specific phantom used was not accounted for.

INNOVATION/IMPACT

PCD-CT is a new technology that provides intrinsic spectral sensitivity in a CT scan, along with dose reduction and higher spatial resolution. Applications such as proton therapy treatment planning are well-positioned to benefit from these capabilities, provided that the quantitative accuracy of PCD-CT is well characterized. This work shows that PCD-CT is highly accurate compared to both a current standard and ground truth SPR values. By improving SPR accuracy, PCD-CT has the potential to enhance proton range confidence and support more precise and reliable proton therapy treatment planning.

CONCLUSIONS

PCD-CT and EID-CT measurements of SPR both agree well with published ground truth, with PCD-CT slightly outperforming EID-CT. The MAPE averaged over all materials and kV setting for was 1.12% and 1.80% for PCD-CT and EID-CT, respectively, suggesting that both scanners yield accurate results for SPR.

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