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Dosimetric Comparison of Proton Therapy Plans Calculated Using Fast Kv Switch Dual Energy CT Versus Single Energy CT

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ABSTRACT

Fast kV-switching dual-energy CT (DECT) has been demonstrated to more accurately predict relative stopping power (RSP) for proton therapy planning over HU-RSP conversion using single-energy CT (SECT). It is essential to evaluate the improvement in tissue characterization, reduction in range uncertainties, and accuracy in the dose calculation. In this study, treatment plans are calculated in phantom on SECT and DECT. A dosimetric comparison to a ground truth reference model is evaluated using a cylindrical head phantom which contained 10 different inserts. Eight separate single field plans were optimized to a central PTV, each ranging through a different insert. The difference in dose and range is calculated from the nominal plan to the reference plan to evaluate the accuracy of RSP calculation using DECT compared to SECT. The D95 for the PTV resulted in an average percent relative error of -0.56% ± 0.19% in DECT and -0.79% ± 0.39% in SECT when calculated on the reference CT. DECT average dose to the OARs 1 mm distal and proximal to the PTV was more accurate than SECT for all plans except for the plan ranging through breast and adipose. The average difference in range when calculated on the reference image is 0.20 mm ± 0.75 mm compared to an average range change of 1.01 mm ± 1.10 mm planned with SECT. The positive value indicates over-ranging in the reference scan into distal structures.

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INTRODUCTION

DECT has been shown to be a promising modality to use for proton therapy planning over the traditional use of SECT. With better tissue characterization and improved RSP determination, DECT can potentially reduce the range uncertainty used for proton therapy planning. In this study, treatment plans each ranging through a different material are optimized separately on a phantom scanned with both DECT and SECT, and the resulting dose distribution is compared to a ground truth CT with known geometry, material density, and composition.

METHODS AND MATERIALS

Acquisition of phantom in DECT and SECT

Ground truth reference scan created using known dimensions, material density, and composition

Plan optimization

- Central cylindrical PTV (DxL 4.6x3.5 cm, V = 62 cc)
- Distal/proximal ROIs 1 mm WET in increments up to 3 mm
- Single field through each insert (total of eight plans)
- DECT and SECT plans were recalculated without re-optimization onto reference scan

Dose calculation evaluation

$$Percent\ Relative\ Error = \frac{\text{Reference Plan} - Nominal\ Plan}{Reference\ Plan} * 100$$

- Positive values indicate underestimation (dose increase in reference plan)
- Negative values indicate overestimation (dose decrease in reference plan)
- Recorded PTV D95, average dose to distal and proximal ROIs
- Range determined from the patient surface to the 47.50 GyRBE isodose line.
- Difference of the nominal plan range from the reference plan range was calculated.

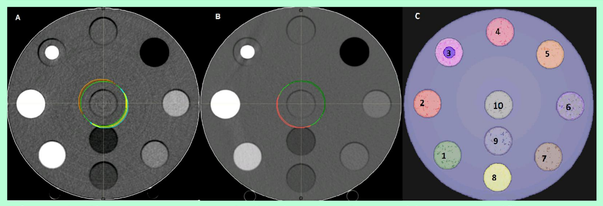

Figure 1. Phantom scans A. DECT showing PTV and beam-specific range margins of 1 mm, 2 mm, and 3 mm. B. SECT showing PTV and beam-specific 1 mm OARs. C. Ground truth reference scan with CT numbers overridden to known mass densities. Insert labels correspond to Table 1.

Table 1. Phantom specifications

ROI	Insert	Z_{eff}	Density (g/cc)	RED
1	Inner Bone	10.11	1.21	1.16
2	Cortical Bone	13.53	1.93	1.78
3	Aluminum	13	2.71	2.36
4	Solid Water	7.59	1.02	1.00
5	Lung	7.58	0.45	0.44
6	Liver	7.59	1.08	1.05
7	Brain	7.4	1.05	1.02
8	Adipose	6.14	0.96	0.94
9	Breast	6.82	0.98	0.97
10	True Water	7.42	1.00	1.00

RESULTS

PTV D95

- DECT: -0.56% ± 0.19%
- SECT: -0.79% ± 0.39%

OARs average

- DECT was closer to the reference plan for all inserts with exception to the Breast+Adipose plan
- Excluding Breast+Adipose plan, average %RE:
  - Distal 1 mm- DECT: 0.6% ± 0.7%; SECT: 1.8% ± 0.4%
  - Proximal 1 mm- DECT: -0.9% ± 0.6%; SECT: -1.7% ± 0.7%.

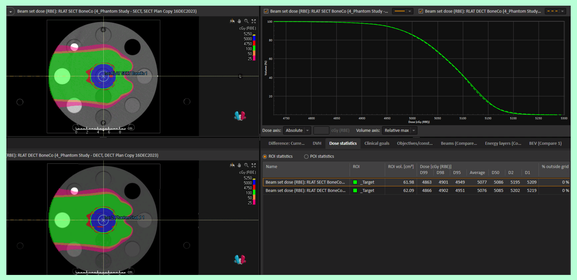

Figure 2. Cortical bone plans for SECT (top) and DECT (bottom) show dosimetrically similar plans with superimposed DVH lines and dose statistics within 0.25%.

Figure 3. Resulting %RE in the reference scan compared to DECT and SECT in the PTV and OARs. Negative = lower dose calculated on reference scan. Positive = more dose calculated on the reference scan.

Table 2. Range Difference (mm) compared to reference.

Plan	SECT Dif (mm)	DECT Dif (mm)
Cortical Bone	2	-0.3
Aluminum	-0.8	0.4
Solid Water	1.4	0.8
Lung	2.7	1.5
Liver	0.5	0.2
Brain	0.7	-0.01
Breast+Adipose	0.2	-1
Inner Bone	1.4	0.2
Average	1.01 ± 1.10	0.22 ± 0.74

DISCUSSION

- SECT on average over-ranged into the distal ROI by 1 mm, vs. DECT average over-range of 0.2 mm.
- Lung plan showed largest deviation in PTV for both DECT (1.5 mm) and SECT (2.7 mm). This is consistent with previous evaluations in lung tissue as having the largest uncertainty.[1]
- Breast+Adipose plan ranged through 2 different material types, resulting in a pullback of 1 mm which lowered the dose to the distal OARs and increased the proximal dose.

Limitations

Simple single-field plans calculated through mostly uniform material with a different insert. This study was not comprehensive to represent the complex heterogeneous conditions that arise in radiation treatment planning in human geometries. To understand the true clinical impact of DECT, planning would need to include a variation of anthropomorphic phantoms and patient studies. However, it was demonstrated that DECT produced D95 values that were in better agreement with the ground truth reference plan than those obtained with planning SECT. This indicates based on our head-sized phantom that on average, DECT has the potential to achieve less range error compared to a similar plan calculated on SECT.

CONCLUSIONS

There was a larger dosimetric difference between SECT and the reference dataset compared to the difference seen between DECT and the reference dataset. On average, the range error was less in DECT than in SECT. In this phantom end-to-end investigation, DECT-based planning produced smaller dose and range deviations relative to the reference dataset than SECT-based plan.

REFERENCES

1 Wang, Hazel, et al. "Evaluation of a Fast kV Switching Dual Energy CT in Deriving Relative Stopping Power Using Tissue Equivalent Phantoms of Various Sizes." Medical Physics, vol. 53, no. 2, Feb. 2026, p. e70288. DOI.org (Crossref), https://doi.org/10.1002/mp.70288.

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