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Quantitative Framework for Adopting DECT with dSPR into a Proton Clinic

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ABSTRACT

Purpose. DECT-derived direct stopping-power ratio (dSPR) can reduce proton range uncertainty, but is often adopted without cross-scanner validation or clearly defined QA. We present a framework to validate dSPR, quantify its reproducibility, and assess its clinical impact.

Methods. Identical DECT protocols were applied on three Siemens CT scanners. Inter-scanner reproducibility was assessed with distal-range (R90) metrics in RayStation. A simplified toy-model plan compared 3.5% and 2.0% assumed range uncertainty.

Results. R90 agreed within ~1 mm/1% for soft-tissue and adipose inserts; higher density and calcium based materials showed larger, scanner dependent variability. Reduced range uncertainty improved distal OAR sparing while maintaining target coverage.

Conclusions. Material and scanner dependent dSPR variability should be characterized before clinical use. Validated range uncertainty reduction can improve OAR sparing. Routine phantom QA is recommended beyond commissioning to confirm consistency over time.

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INTRODUCTION

Dual-energy CT (DECT) enables direct stopping-power ratio (dSPR) prediction, offering improved tumor delineation and reduced proton range uncertainty relative to single energy CT.

A principal claimed benefit of dSPR is a scanner independent stopping-power curve for proton planning. In practice, however, such tools are frequently introduced into clinical workflows **without comprehensive validation across scanner platforms or clearly defined QA strategies.**

This work presents a systematic, quantitative framework to validate DECT-derived dSPR, evaluate its inter-scanner reproducibility, and assess the dosimetric benefit of reduced range uncertainty in proton therapy.

METHODS AND MATERIALS

Phantoms & scanners. Commercial tissue equivalent phantoms (Sun Nuclear Advanced Electron Density) and in house phantoms (bone, fat, water, lung) were imaged. Identical DECT acquisition and reconstruction protocols were applied across three Siemens scanners: Somatom (CT1), go.Open Pro (CT2), and Definition Edge (CT3).

Range endpoint. Single-spot depth-dose profiles were computed in RayStation 2023B (Monte Carlo). Scanner consistency was quantified by the distal R90 range, with CT3 as reference. RTDose files were exported to Python for task-specific comparison not available in commercial TPS.

Dosimetric toy model. A water-override pyramid target with two distal OARs (1 cm and 2 cm beyond the apex) was planned with identical beam geometry. Two range-uncertainty assumptions were compared: conventional 3.5% and reduced 2.0%.

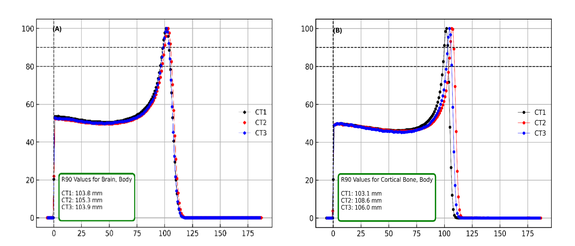

Figure 1. Figure 1: Depth–dose curves for (A) Brain and (B) Cortical Bone inserts acquired on CT1, CT2, and CT3, with R90 (distal 90% dose position) indicated for each scanner.

RESULTS

Inter-scanner reproducibility. R90 agreement was within ~1 mm/1% for soft-tissue and adipose-equivalent inserts (Brain, Liver, Breast, Solid Water, Adipose), indicating stable distal-range behavior (Figure 1).

Larger, scanner-dependent variability was observed for higher-density and calcium-based materials, with inter-scanner R90 spreads up to ~5.5 mm for Cortical Bone and ~7.5 mm for Lung LN-300 (Table 1).

Dosimetric impact. In the toy model, target coverage was comparable for both scenarios. The 2.0% plan reduced dose to both distal OARs, with the larger reduction for the OAR closest to the distal edge (Figures 2& 3).

Table 1. Distal-range (R90, mm) across three scanners (CT3 = reference); Spread = max − min.

Insert	CT1	CT2	CT3	Spread
Brain	103.8	105.3	103.9	1.5
Liver	103.9	105.2	104.9	1.3
Breast	105.9	106.5	105.6	0.9
Solid Water	104.4	105.0	104.0	1.0
Adipose	105.0	105.5	106.0	1.0
Lung LN-450	112.3	112.6	108.1	4.5
Lung LN-300	114.6	118.6	111.1	7.5
Cortical Bone	103.1	108.6	106.0	5.5
Inner Bone	103.1	106.3	104.6	3.2
$CaCO_3$ 30%	100.4	103.6	102.5	3.2
$CaCO_3$ 50%	104.2	107.1	105.8	2.9

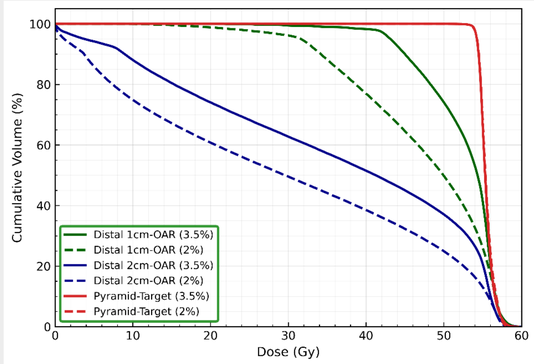

Figure 2. Dose–volume histograms for the distal 1 cm OAR, distal 2 cm OAR, and pyramid target: 3.5% (solid) vs 2% (dashed) plans; cumulative volume (%) over 0–60 Gy.

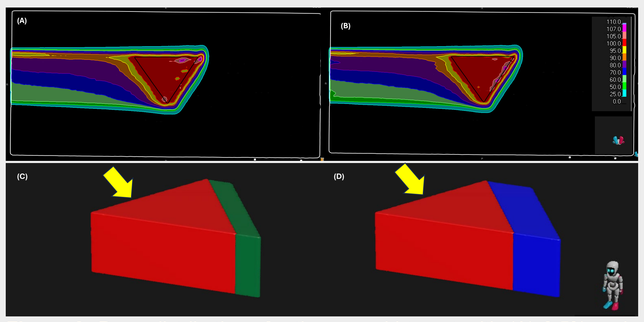

Figure 3. Dose distributions for the pyramid target with (A) 3.5% and (B) 2% range uncertainty; phantom external contour in white. (C, D) 3D representations showing the distal 1 cm OAR (green) and 2 cm OAR (blue); arrow indicates beam direction.

DISCUSSION

Phantom-based validation revealed material- and scanner dependent variability in DECT-derived dSPR. Soft-tissue inserts were reproducible, whereas high density and calcium-based materials retained residual scanner dependence that should be characterized before clinical use.

This variability also has implications for multi-institutional studies, where differences in scanner performance may propagate into range predictions.

Site specific measurements with a multilayer ion chamber supported reducing the clinical range-uncertainty margin from 3.5% to 2.0% for DECT eligible sites (e.g., brain, head and neck, pelvis), with all scanners in agreement.

KEY TAKEAWAYS

1. **Soft tissue is reproducible:** R90 agrees within ~1 mm/1% across all three scanners.
2. **Dense media are not:** R90 spreads reach ~5.5–7.5 mm for bone/calcium, characterize before clinical use.
3. **Tighter margins help:** 3.5% → 2.0% lowers distal-OAR dose with no loss of target coverage.
4. **QA it routinely:** phantom-based dSPR checks monthly, beyond initial commissioning.

CONCLUSIONS

DECT-derived dSPR shows material- and scanner-dependent variability that must be characterized prior to clinical use.

Validated reductions in range uncertainty (3.5% → 2.0%) can translate into improved sparing of organs at risk distal to the target without compromising coverage.

Routine phantom-based QA is recommended beyond initial commissioning, performed monthly alongside CT number (HU) constancy checks, to confirm consistency over time.

REFERENCES

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