

Accuracy of Relative Electron Density and Stopping Power Ratio Estimation Using Dual-Energy Cone-Beam CT Virtual Monoenergetic Images

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PURPOSE

Anatomical variations during treatment cause dose discrepancies that severely impact proton therapy accuracy due to the sharp Bragg peak. To address this, we developed a novel Dual-Energy Cone-Beam CT (DE-CBCT) technique to generate Virtual Monoenergetic Images (VMIs) for online Adaptive Radiotherapy (ART)[1]. Head, chest, and abdomen phantoms with tissue-equivalent inserts were scanned using DECT, Twin-Beam DECT (TB-DECT), and DE-CBCT to establish CT number-to-RED/SPR conversion curves and evaluate proton dose calculation accuracy. Although DE-CBCT VMIs exhibited higher noise, incorporating a Block Matching 3D (BM3D)[2] denoising algorithm and utilizing an 80/140 kVp acquisition pair effectively mitigated noise, yielding an SPR prediction performance comparable to TB-DECT, particularly in the head region. Despite limitations regarding Halcyon CBCT image quality, fixed beam parameters, and potential motion artifacts from consecutive scans, this study represents the first successful utilization of a standard Linac CBCT for VMI-based SPR prediction and dose validation. The developed software will be open-sourced on GitHub to lower technical barriers for proton therapy centers worldwide.

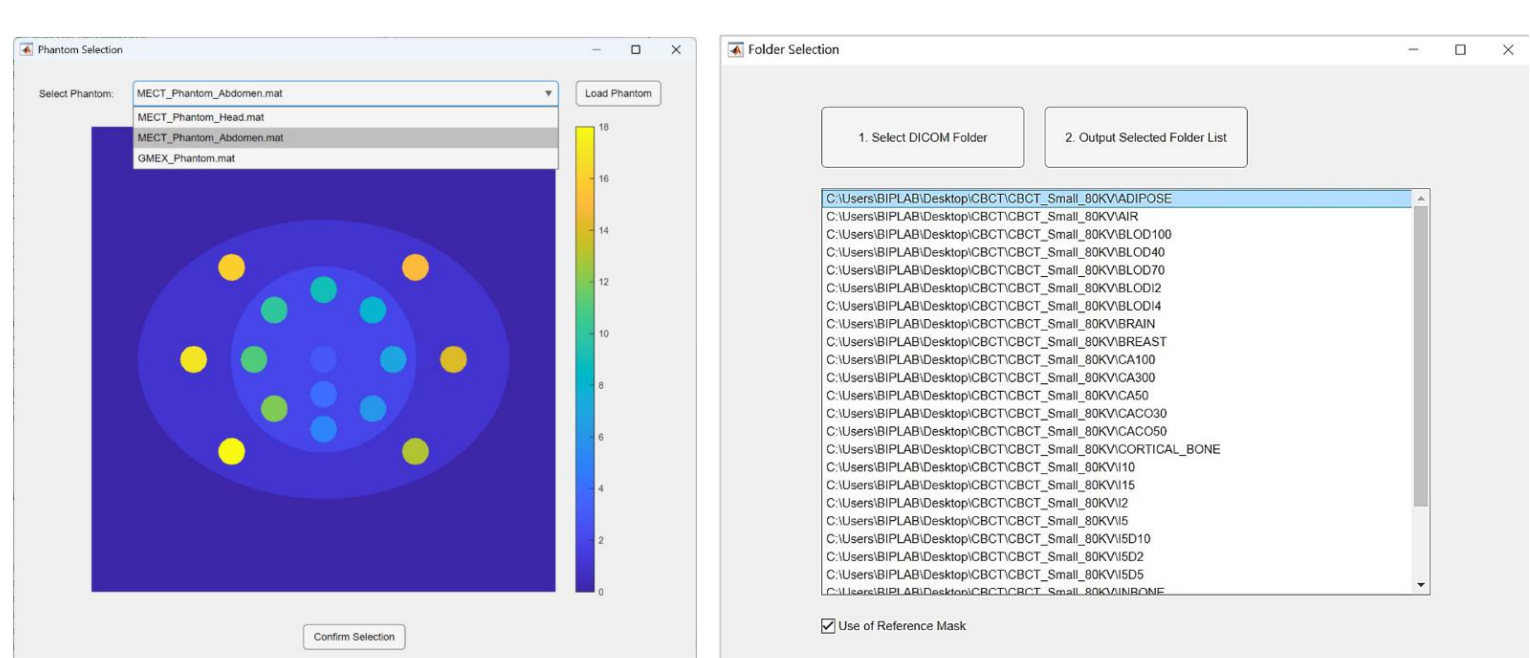


Figure 1. Graphical User Interface (GUI) for automated calculation of CT number

MATERIALS & METHODS



Scanned using DECT, TB-DECT, and DE-CBCT systems for comparison with standard DECT.

Estimate energy-dependent weighting factors (α) for DE-CBCT and generate 40–150 keV Virtual Monoenergetic Images (VMIs).

Apply the BM3D denoising algorithm to smooth low-energy VMIs, then perform stoichiometric calibration[3] to derive the Hounsfield look-up table (HLUT) for CTN-SPR/RED curves.

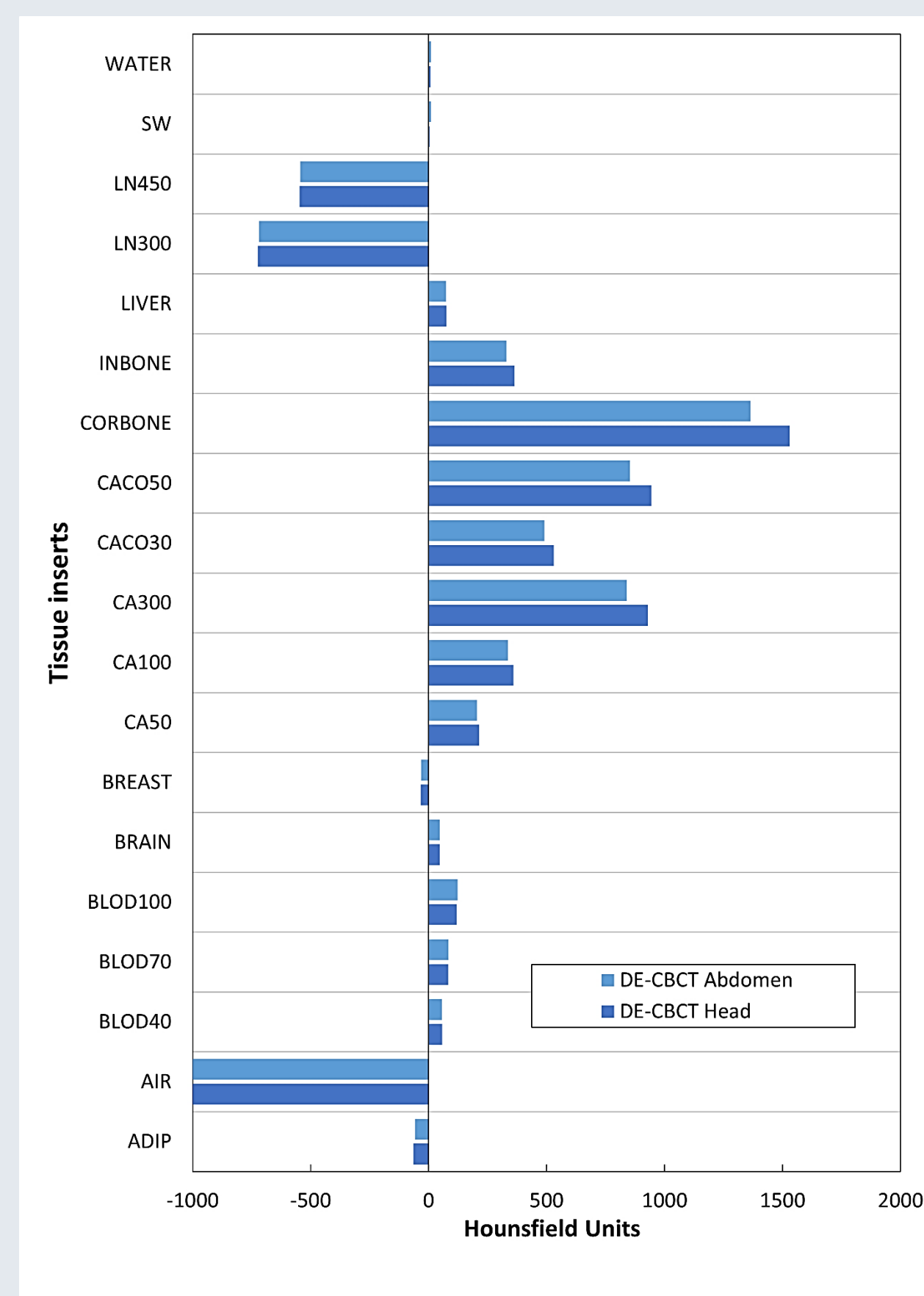


Figure 7. HU values of tissue-equivalent inserts

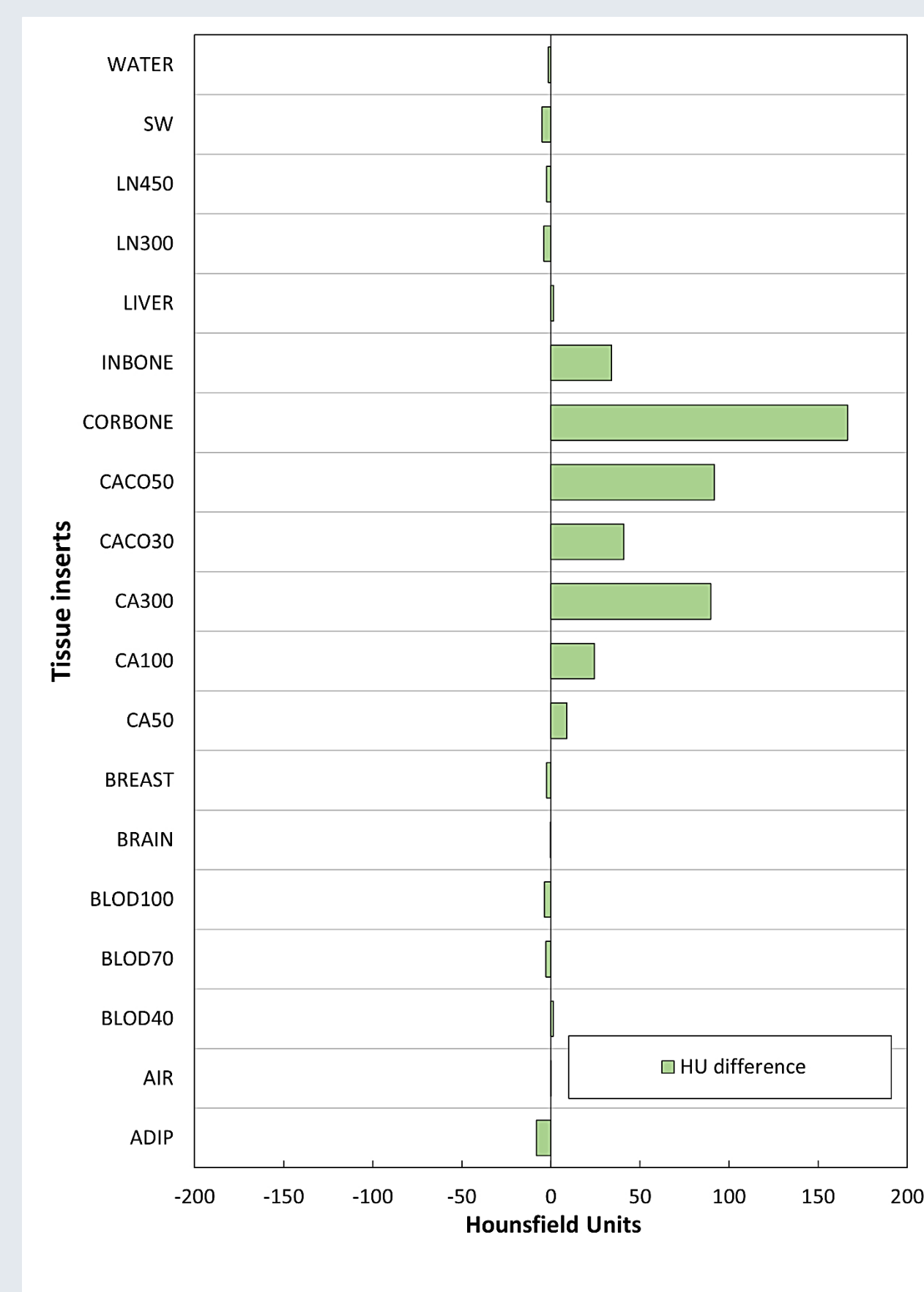


Figure 8. HU differences for different phantom sizes

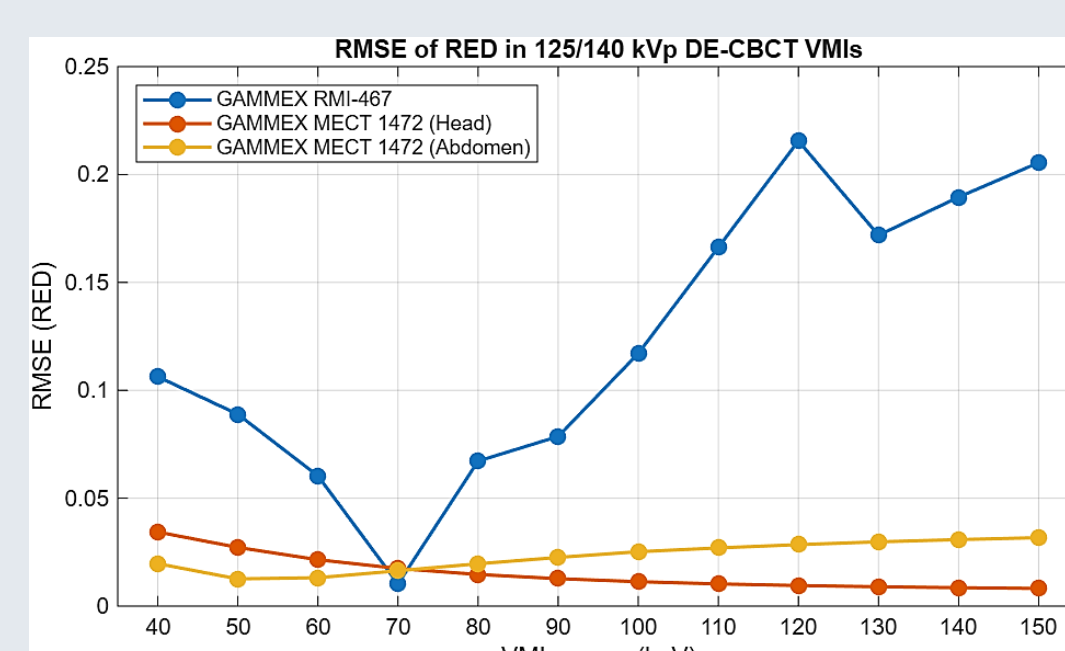


Figure 9. RMSE of relative electron density (RED)

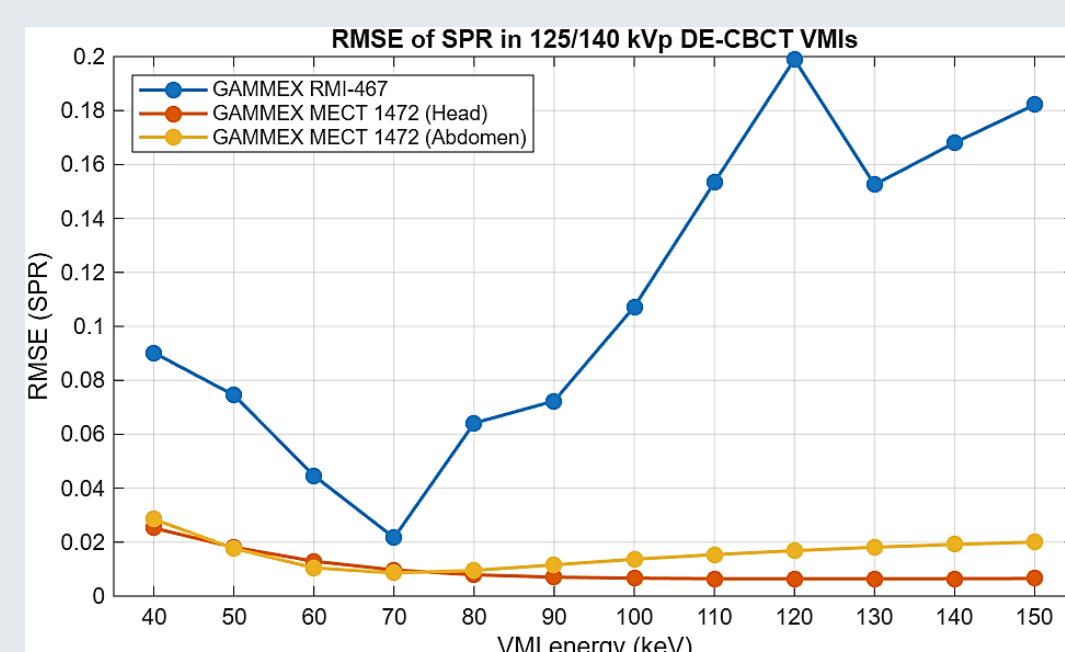


Figure 10. RMSE of stopping power ratio (SPR)

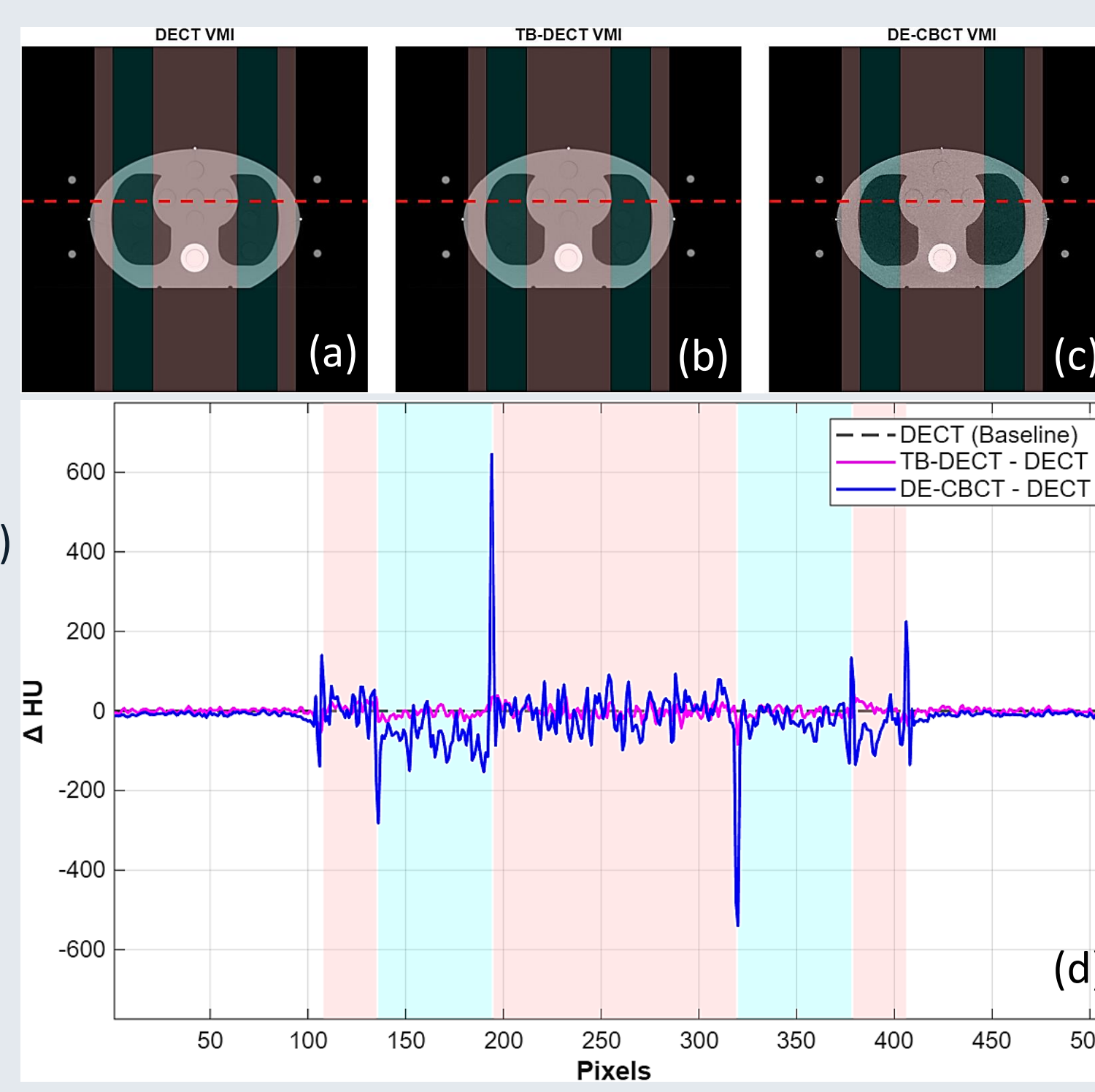


Figure 11(a)-(d). Analysis of the CIRS THORAX Phantom. (a) DECT VMI, (b) TB-DECT VMI, (c) DE-CBCT VMI at 60 keV, and (d) Δ HU profiles

RESULTS & DISCUSSION

- Artifacts & Phantom Size:**
 - In **Figures 7 & 8**, scatter and beam-hardening significantly impacted CTN stability under CBCT 140 kVp, causing 100–200 HU deviations in dense bone. However, soft tissue variations remained within 50 HU (40–50 keV VMI) after applying BM3D denoising with consistent weighting factors.
 - Axial thickness limitations were evident in the GAMMEX RMI-467 phantom, which showed the most inaccurate parameter estimations under CBCT geometry due to its limited phantom thickness (**Figures 9 & 10**).
- VMI Profile Performance (125/140 kVp at 60 keV):**
 - As shown in **Figure 11(a)-(d)**, the mean absolute error (MAE) of HU values compared with standard DECT was 9.1 HU for TB-DECT and 35.8 HU for DE-CBCT in the CIRS THORAX phantom, with higher deviations observed only at the lung boundaries. Overall, the profile of DE-CBCT remains highly comparable to regular clinical protocols.
- Optimization & Denoising (80/140 kVp DE-CBCT):**
 - The 80/140 kVp DE-CBCT acquisition pair significantly outperformed 100/125 kVp at 70 keV in the CIRS HEAD phantom (**Figure 12**), effectively suppressing the higher inherent noise of CBCT.
 - As shown in **Figure 13**, the 80/140 kVp DE-CBCT VMI at 70 keV exhibited a dose difference of less than 10% relative to the standard DECT VMI.
 - By employing the BM3D denoising algorithm, the standard deviation (STD) was successfully reduced by 25 HU, while the HU values were maintained within a range of ± 5 HU (**Figures 14 & 15**).
- HLUT & SPR/RED Conversion:**
 - For VMI energies ≥ 70 keV, DE-CBCT achieved lower RED/SPR RMSEs, reaching a minimum RED RMSE of 0.011 at 150 keV (**Figure 16**).
 - DE-CBCT VMI parameters were comparable to DECT/TB-DECT, even yielding the lowest RMSE of 0.005 for SPR estimation (**Figure 17**), reflecting the high accuracy of our developed image-based calibration strategy.
- Limitations & Clinical Scope:**
 - DE-CBCT currently requires consecutive dual scans due to the lack of clinical protocols, posing motion artifact risks in thoracic and pelvic regions. Large phantoms also exceeded the CBCT FOV, restricting acquisitions to 125/140 kVp.
 - The proposed technique is currently best optimized for stationary head regions.

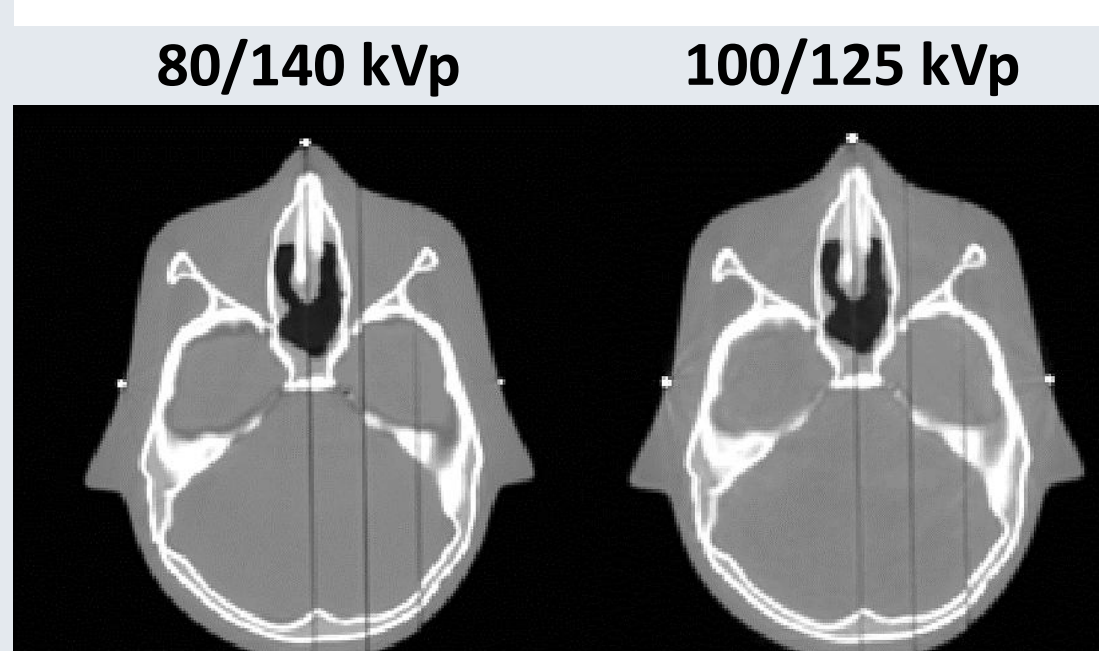


Figure 12. Comparison of VMIs synthesized from (a) 80/140 kVp and (b) 100/125 kVp acquisitions

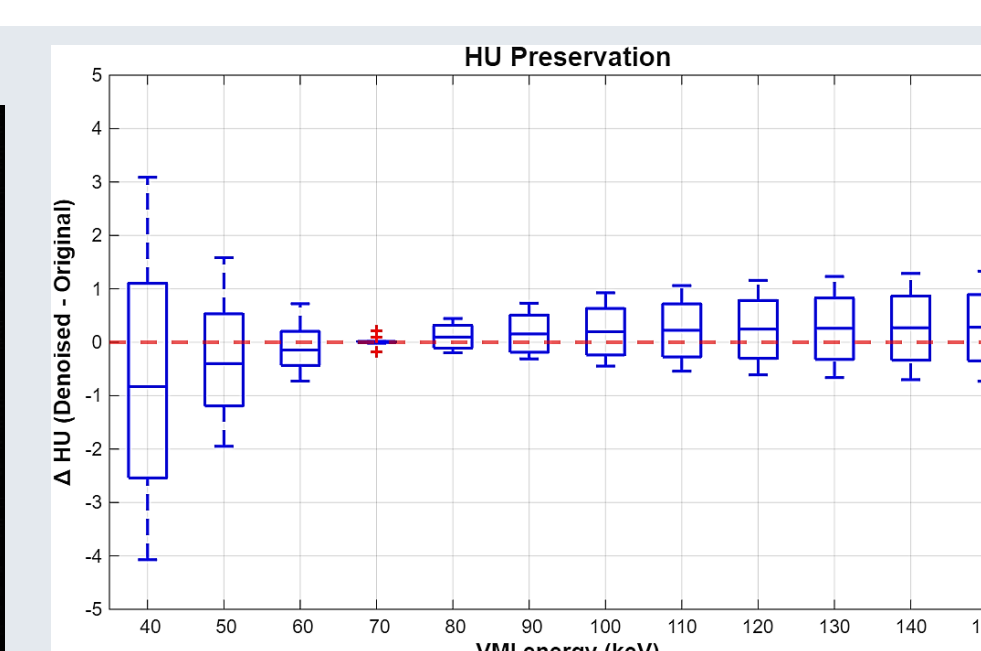


Figure 14. HU difference of GAMMEX MECT 1472 Phantom

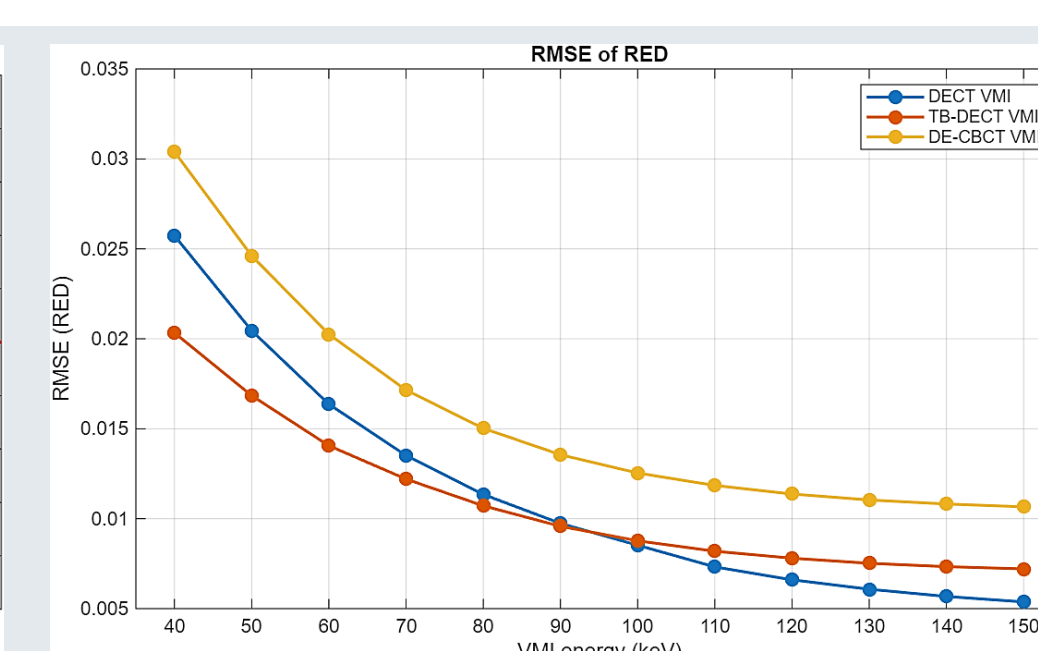


Figure 16. RMSE of RED for GAMMEX MECT 1472 Phantom

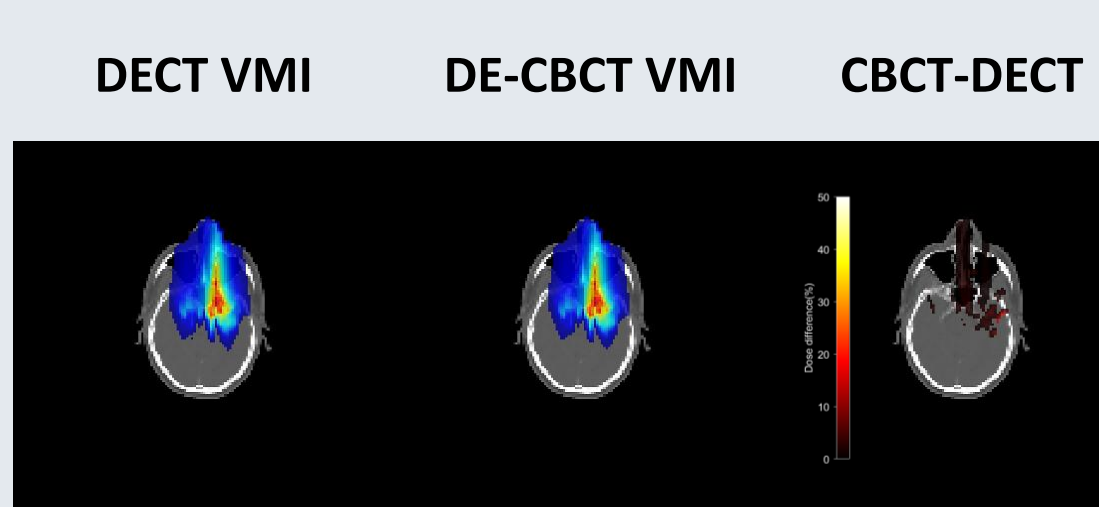


Figure 13. Dose distribution at 70 keV from 80/140 kVp acquisition

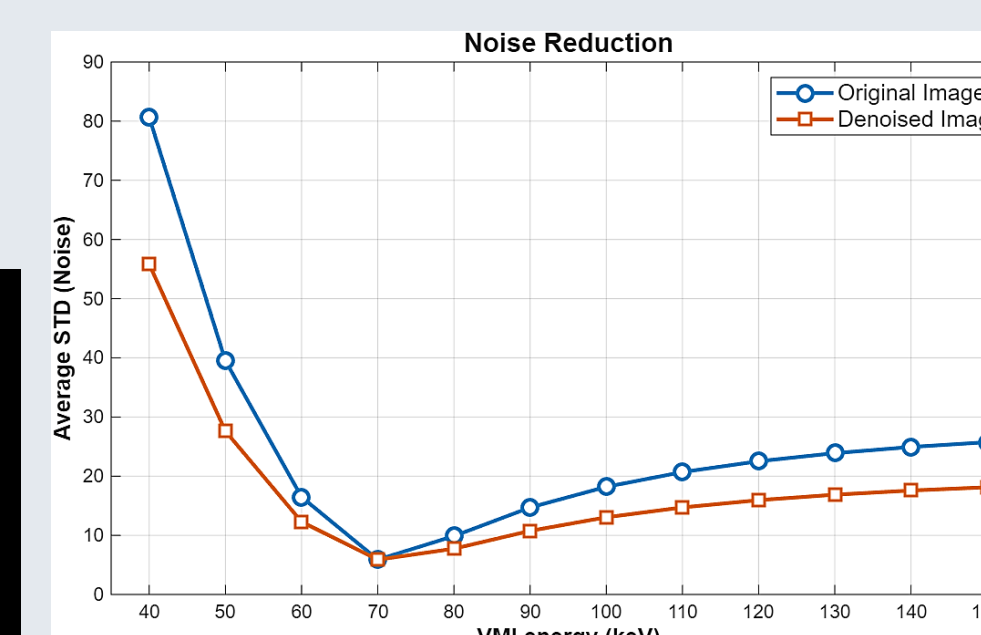


Figure 15. STD comparison of GAMMEX MECT 1472 Phantom

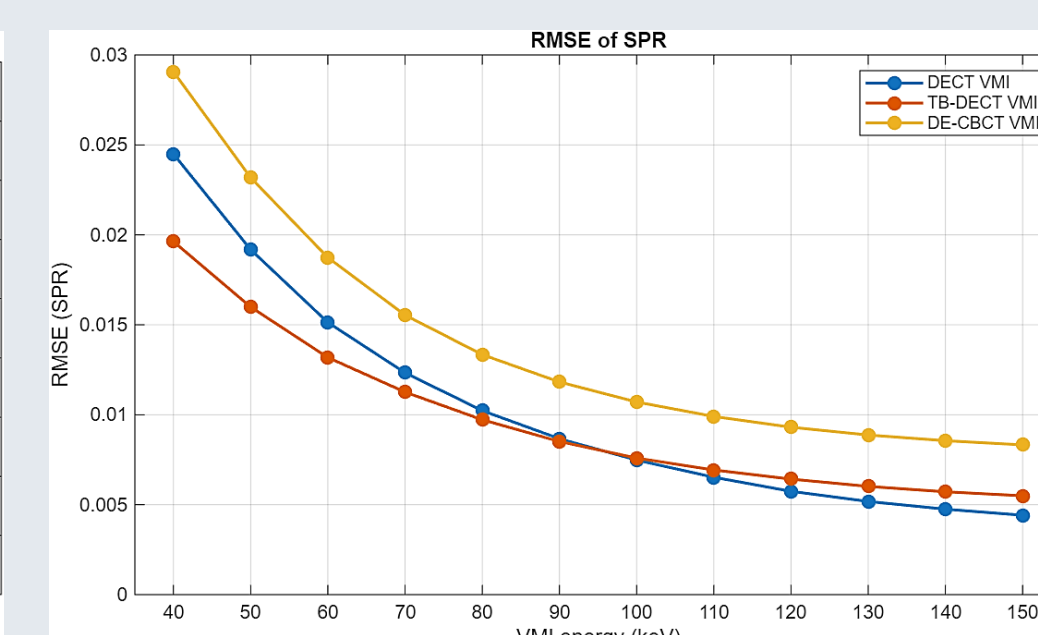


Figure 17. RMSE of SPR for GAMMEX MECT 1472 Phantom

CONCLUSIONS

This study validates the feasibility of Dual-Energy CBCT (DE-CBCT)-derived Virtual Monoenergetic Images (VMIs) for accurate RED and SPR prediction. This approach provides a practical and hardware-accessible alternative to DECT for adaptive radiotherapy, with future potential for AI-enhanced image quality optimization.

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