Deep Learning-Based 4D Dual-Energy CBCT Generation for Material Decomposition

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CLINICAL MOTIVATION / PURPOSE

NEED

Phase-aligned low- and high-energy 4D-CBCT is required to support dual-energy material decomposition in moving anatomy.

PROPOSAL

Predict 150-kVp 4D-CBCT from 80-kVp data with a 3D U-Net, creating phase-aligned dual-energy pairs without a scanner upgrade.

Evaluate synthesis in adult internal and pediatric external tests, then quantify downstream RED/RSP accuracy.

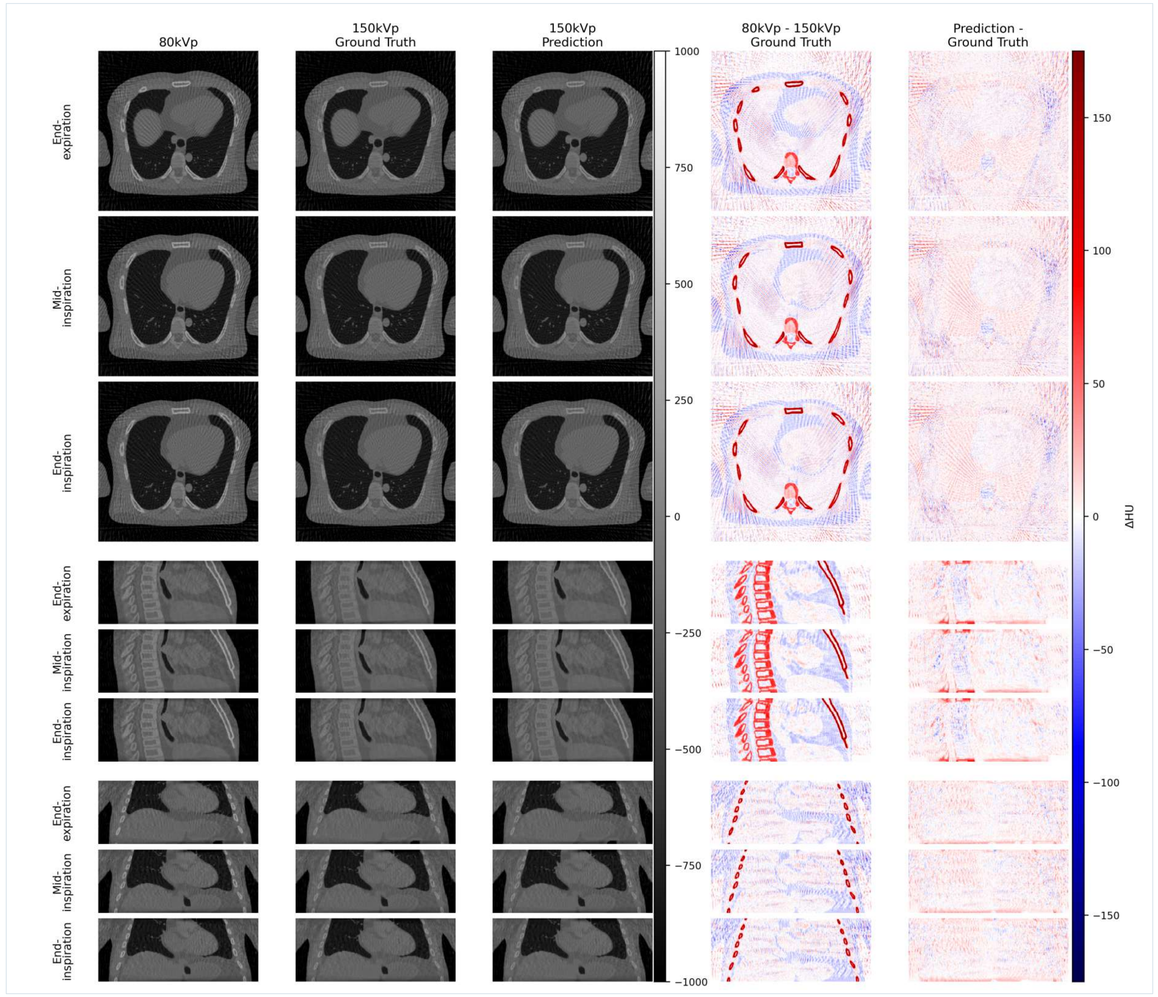
DATASET AND METHODS

- 10 adult XCAT subjects: 5 male + 5 female; three breathing curves per subject; 10 phase bins.
- TIGRE reconstructed paired 80-kVp and 150-kVp volumes: 30 paired 4D sets and 300 volumes per energy.
- 3D U-Net with mean-squared-error loss; subject-level 8 / 1 / 1 train / validation / internal-test split.
- Single-channel 80-kVp input compared with 80-kVp + sparse 150-kVp phase-misaligned two-channel input.
- External test: four pediatric XCAT phantoms spanning ages 1, 10, and 15 years.

STUDY WORKFLOW

XCAT adults + pediatric → TIGRE 80 / 150 kVp → Phase-matched 4D DE-CBCT → 3D U-Net 1- vs 2-channel → Synthetic 150-kVp → RED / RSP decomposition

ADULT INTERNAL VALIDATION — REPRESENTATIVE 4D RESULT



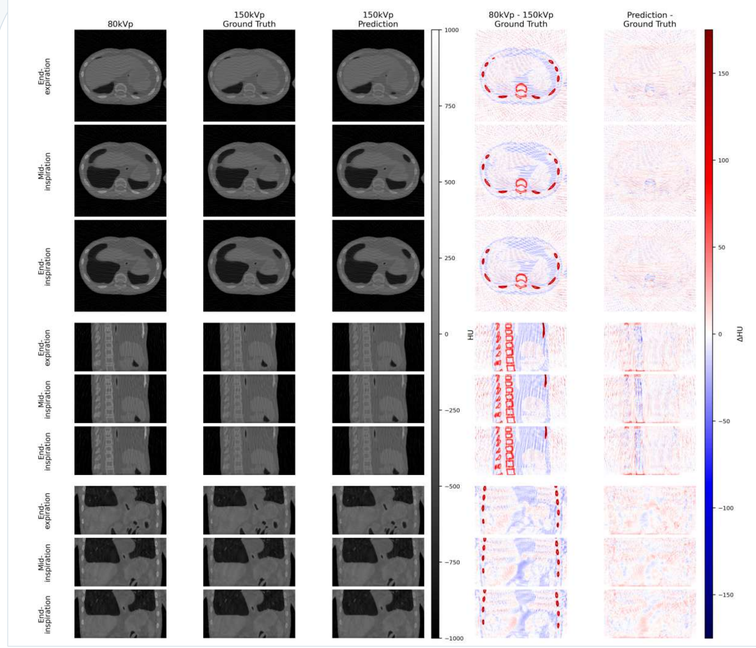
Comparison between predicted 150-kVp images and ground truth in an adult test set.

INPUT STRATEGY COMPARISON

Adult internal	NMAE	NCC	SSIM
Single-channel	0.005279	0.9994	0.9902
Two-channel	0.004790	0.9996	0.9902

Two-channel input modestly improved the reported NMAE and NCC. SSIM remained similar between the two strategies.

PEDIATRIC EXTERNAL VALIDATION



Comparison between predicted 150-kVp images and ground truth in a pediatric test set(10-year-old).

METRIC SUMMARY

IMAGE SYNTHESIS

Adult internal
Single-channel

NMAE	0.005279
NCC	0.9994
SSIM	0.9902

Pediatric external

NMAE	0.004124
NCC	0.9997
SSIM	0.9906

MATERIAL DECOMPOSITION

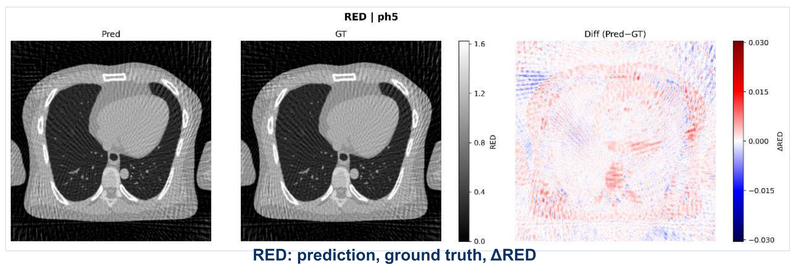
RED
NMAE 0.0006512
NCC 0.99988
SSIM 0.99989

RSP
NMAE 0.0006761
NCC 0.99986
SSIM 0.99979

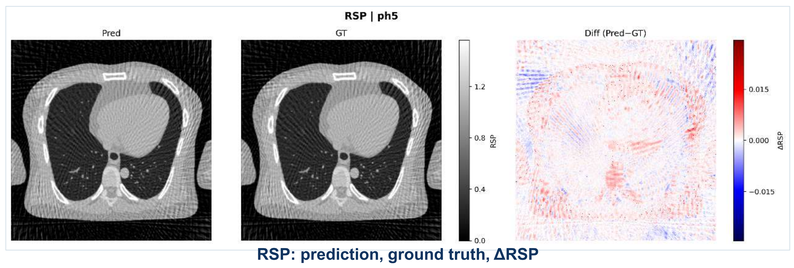
Synthesis metrics quantify predicted 150-kVp images.

RED/RSP metrics quantify downstream decomposition maps.

MATERIAL DECOMPOSITION — ADULT INTERNAL TEST



RED: prediction, ground truth, ΔRED



RSP: prediction, ground truth, ΔRSP

KEY FINDINGS

- Adult internal synthesis closely matched the paired 150-kVp ground truth.
- The two-channel strategy modestly improved the reported NMAE and NCC.
- Pediatric external and RED/RSP results retained high similarity to ground truth.

CONCLUSION

This study demonstrates the feasibility of phase-aligned 4D DE-CBCT synthetization without scanner upgrade, displaying satisfactory generalizability from adult to paediatric data and accurate downstream RED/RSP maps.

LIMITATIONS

- Validation is limited to simulated XCAT data.
- Adult XCAT dataset includes only 10 subjects while pediatric external testing includes only 4.

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