Unlocking on-Board Dual-Energy: Fast & Robust Material Decomposition for the kV Dual-Layer Imager

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CONTEXT

- Modern radiotherapy relies on **daily imaging** for precise patient positioning. Systems are evolving from conventional single-energy to **dual-energy capabilities** to improve tissue characterization.
- On-board dual-energy imaging leverages energy-dependent X-ray attenuation to perform planar and CBCT **material decomposition**, effectively isolating soft tissue from bone.
- Conventional dual-energy material decomposition relies on an ill-conditioned inverse problem. This inherently **amplifies noise** and severely **degrades the signal-to-noise ratio**.
- This noise amplification directly impairs the performance of noise-sensitive applications such as **markerless tumor tracking**.
- This project aims to develop techniques to minimize noise amplification, improving the quality of material decomposed images.

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OBJECTIVES

To introduce **PRISM** [1], an open-source Julia framework designed for real-time, iterative, regularized dual-energy **material decomposition** on a novel prototype of **on-board kV dual-layer imager** [2].

RESEARCH ARTICLE — MEDICAL PHYSICS
PRISM: An open-source framework for regularized material decomposition on a novel kV dual-layer imager

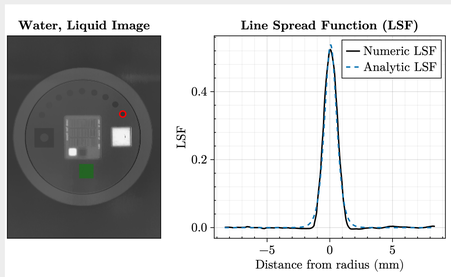
METHODS AND MATERIALS

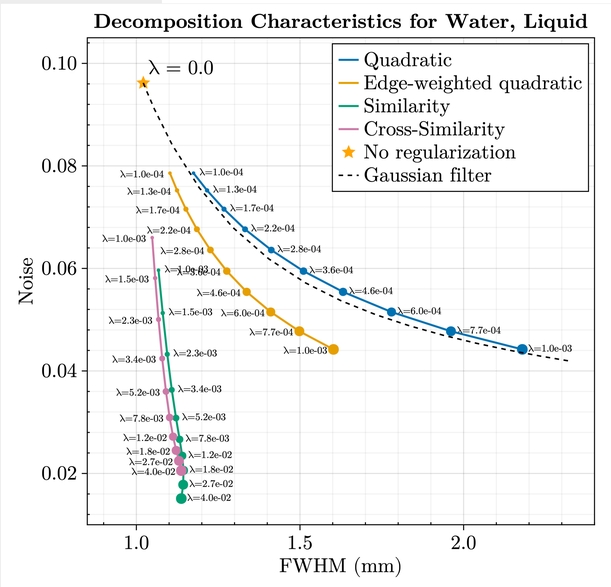
- A **penalized weighted least squares** objective function was implemented to perform iterative material decomposition:

$$\min_{\vec{x}} F(\vec{x}) = (\mathbf{A}\vec{x} - \vec{x_0})^T \mathbf{V}^{-1} (\mathbf{A}\vec{x} - \vec{x_0}) + \lambda R(\vec{x})$$

- **Four regularization strategies** R were investigated: quadratic, edge-weighted quadratic, non-local similarity, and the proposed cross-similarity, which enforces consistency in both spatial and spectral domains.
- To evaluate performances, dual energy projections were acquired using the dual-layer imager and preprocessed:
  - ❑ **TOR-18FG phantom** to quantify the trade-off between noise and spatial resolution (defined as the Line Spread Function FWHM) and signal bias
  - ❑ **Patient thoracic projections**
- Computation times were compared between a CPU sparse-matrix implementation and a custom **GPU matrix-free implementation**.

↘ **Figure 1**: Spatial resolution (FWHM of the LSF) versus noise for the four regularization strategies and the two material-decomposed TOR-18FG images (water and bones), for increasing λ values.

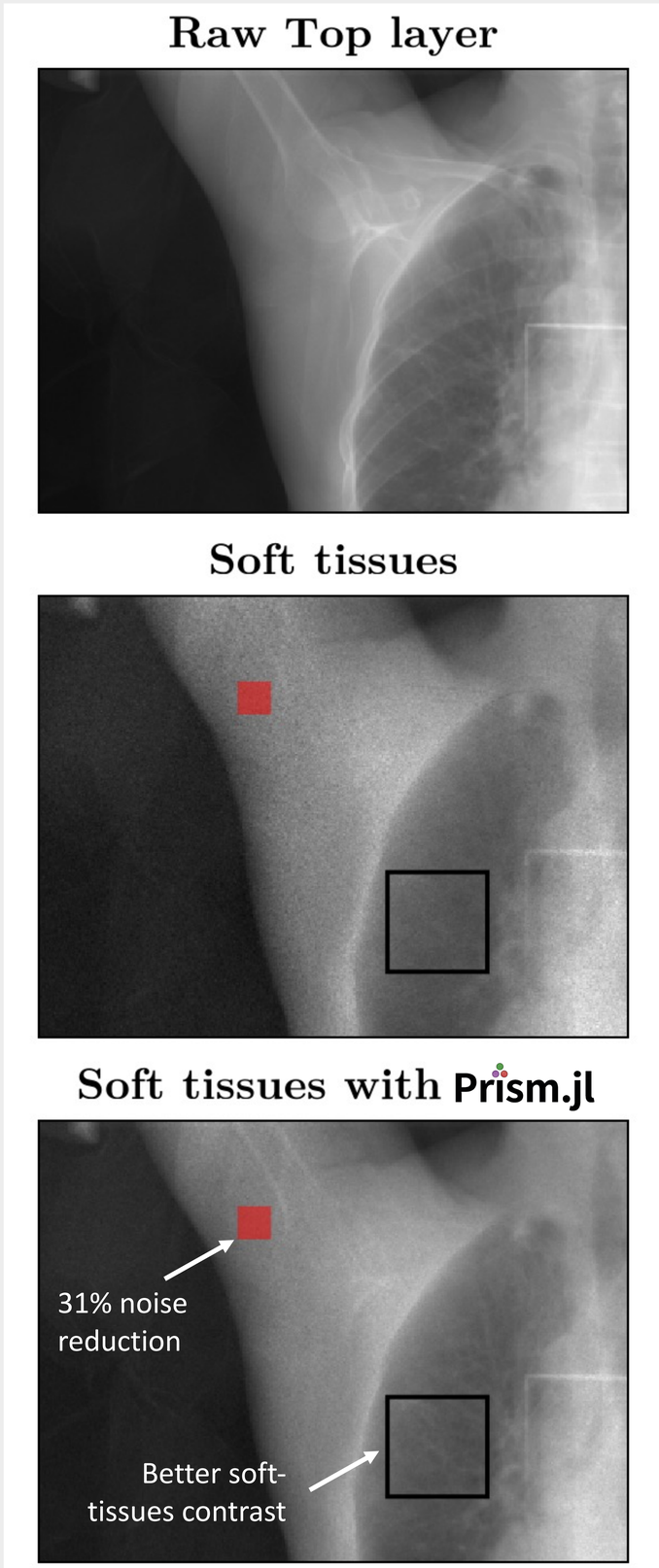




RESULTS

- The new **cross-similarity regularization**
  - ❑ achieved up to a 5-fold noise reduction in water-equivalent images while preserving spatial resolution, outperforming local regularization methods (**Figure 1**).
  - ❑ maintained **minimal bias** (below 1%)
- In patient images, cross-similarity enhanced soft-tissue visibility and **preserved fine lung structures** better than local methods (**Figure 2**).
- The GPU matrix-free implementation achieved **decomposition times under 50 ms**, approximately two order of magnitude faster than on CPU (**Figure 3**)

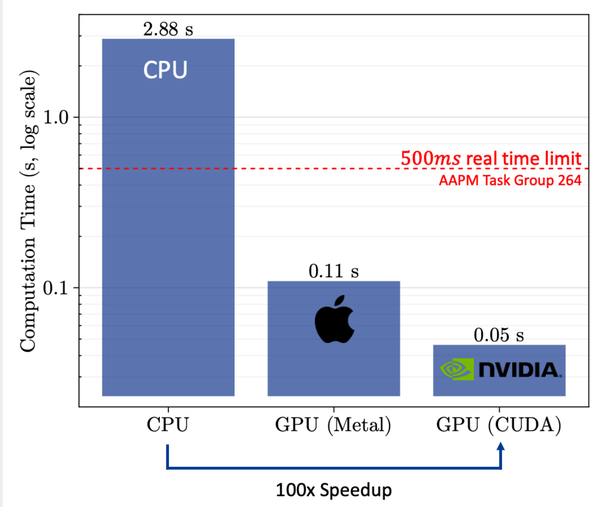
↓ **Figure 2**: Raw top layer and bone-removed patient's thorax images.



DISCUSSION

- Compared to other approaches (sequential or fast kV-switching), the dual-layer design eliminates the risk of **image misregistration** and may **reduce imaging dose**.
- Scatter can significantly impact decomposition quality, and further investigation on the impact of **scatter correction** are needed.
- Future work could expand the framework to a **fully polychromatic model** for quantitative tissue thickness assessment.

↓ **Figure 3**: Computation time of the cross-similarity-based decomposition for the sparse-matrix implementation on CPU and the matrix-free implementation on GPU (Apple Metal and Nvidia CUDA). The GPU matrix-free implementation enabled images generation in less than 50 ms on a Nvidia RTX 3090, compared to approximately 3000 ms for the optimized CPU implementation..



CONCLUSIONS

- Our open-source **PRISM framework** provides a robust tool for high-quality dual-energy material decomposition.
- The novel cross-similarity regularization offers **superior noise suppression** and resolution preservation compared to conventional methods.
- With sub-50 ms processing times, the GPU-accelerated implementation satisfies the latency requirements for **real-time clinical applications** such as intra-fraction markerless tumor tracking.

Free and open-source

REFERENCES

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