Estimation of Proton Stopping Power from Optimized Combinations of Virtual Monoenergetic Images Generated by Dual-Energy CT

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Mohsen Beikali Soltani[1,2], Esther Bär[3,4], Edrine Damulira[1,2], Hugo Bouchard[1,2]

[1]Department of Physics, Université de Montréal, Montréal, QC, Canada [2]Centre de recherche du Centre hospitalier de l'Université de Montréal, Montréal, QC, Canada, [3]Department of Medical Physics and Biomedical Engineering, University College London, London, UK, [4]Radiotherapy Physics, University College London Hospitals NHS Foundation Trust, London, UK

Université de Montréal

ABSTRACT

Previous image-based dual-energy CT (DECT) methods for proton stopping power ratio (SPR) estimation typically rely on predefined pairs of virtual monoenergetic images (VMIs). In this work, principal component analysis (PCA) is applied to VMIs reconstructed from 50 to 200 keV to generate two eigenimages that optimally represent the variance information contained in the full VMI dataset.

The method is experimentally evaluated using the Gammex-467 tissue characterization phantom scanned on a Philips Spectral CT 7500 system.
The first two eigenimages captured 99.5% of the total variance across the VMI dataset and yielded lower RMS errors in electron density relative to water (ρ_e) and SPR estimation than both the 50/200 keV VMI pair and scanner-derived estimates.

These findings demonstrate the potential of PCA-derived eigenimages for quantitative DECT-based tissue characterization.

INTRODUCTION

Accurate estimation of proton stopping power ratio (SPR) is essential for reducing range uncertainties in proton therapy treatment planning. Conventional single-energy CT (SECT) methods rely on a one-to-one relationship between CT number and tissue composition, which suffers from intrinsic degeneracy because different tissues can exhibit similar CT numbers. Dual-energy CT (DECT) partially resolves this limitation by providing additional spectral information for tissue characterization and SPR estimation.

Previous image-based DECT approaches estimate SPR using a predefined pair of virtual monoenergetic images (VMIs) [1,2]. However, modern DECT scanners generate a large set of VMIs spanning a wide energy range and selecting only two predefined energies discards potentially useful information contained in the remaining images. Furthermore, no single VMI pair is necessarily optimal for all tissue types because different materials exhibit distinct energy-dependent attenuation characteristics.

In this work, principal component analysis (PCA) is proposed to exploit the full VMI dataset and derive two independent component images, referred to as eigenimages. The objective of this study is to experimentally evaluate whether these PCA-derived eigenimages improve electron density (ρ_e) and SPR estimation compared with previously suggested VMI pairs and scanner-derived quantitative maps.

METHODS AND MATERIALS

Phantom imaging is performed using the Gammex-467 tissue characterization phantom (Gammex Inc., Middleton, WI) containing 13 tissue-equivalent inserts spanning a range of electron densities and elemental compositions. The phantom is scanned on a Philips Spectral CT 7500 dual-layer detector CT scanner (Philips Healthcare, Best, the Netherlands). Sixteen VMIs are reconstructed at energies ranging from 50 to 200 keV in 10 keV increments. PCA is applied to the CT numbers of the tissue-equivalent inserts across all VMIs to identify the dominant spectral components (Figures 1-3). The first two principal components are subsequently used to construct two independent component images, referred to as eigenimage 1 and eigenimage 2.

The eigenmaterial decomposition (EMD) framework [3] is applied to the eigenimages to estimate voxel-wise ρ_e and SPR (Figure 4). Performance is evaluated using leave-one-out cross-validation, in which each phantom insert is excluded from the calibration dataset and subsequently estimated using the remaining inserts. Estimated ρ_e and SPR values are compared with reference data and with results obtained using (i) a previously suggested 50/200 keV VMI pair and (ii) scanner-derived quantitative maps.

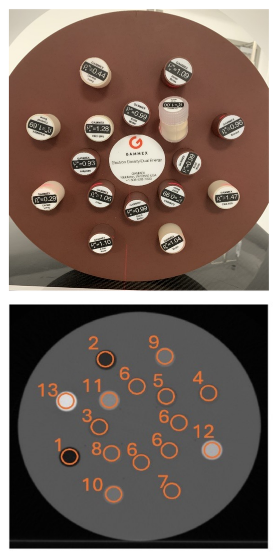

Figure 1. Gammex-467 phantom (top) and corresponding ROIs used for PCA (bottom).

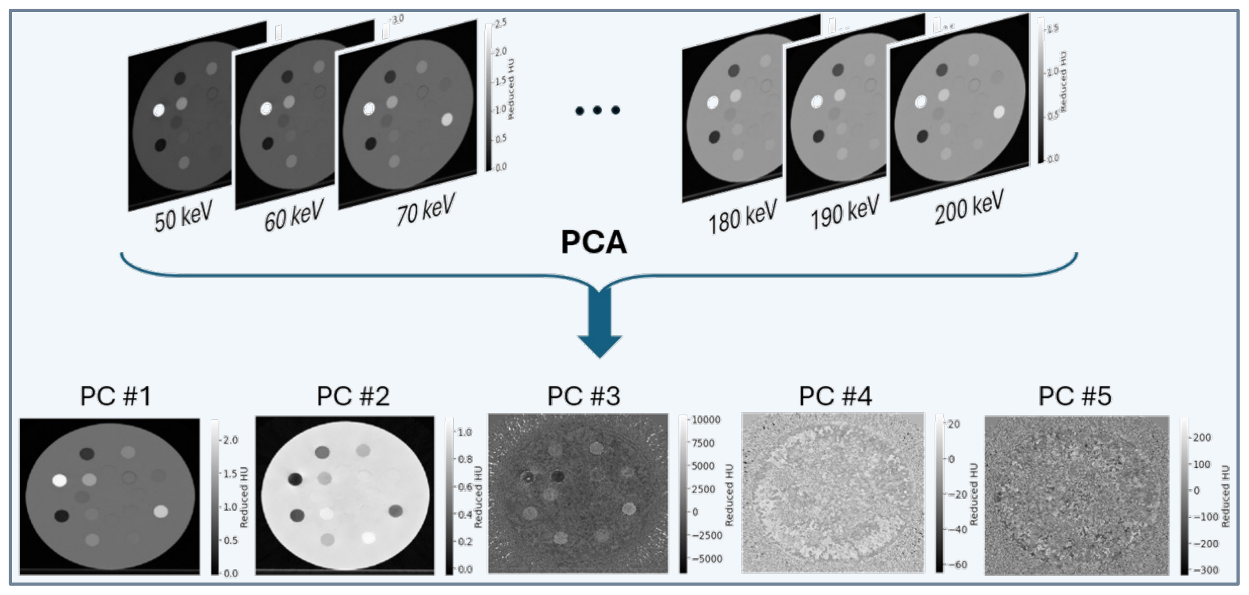

Figure 2. VMIs (top) and PCA-derived PC images (bottom). PC1 and PC2 capture the dominant information; higher-order PCs primarily represent noise.

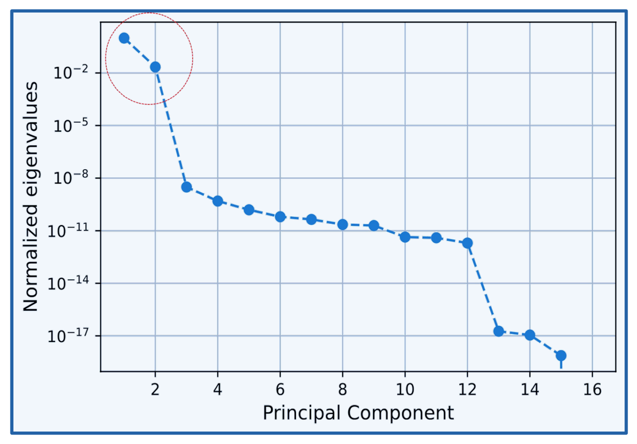

Figure 3. Normalized eigenvalues of the principal components obtained by applying PCA to the 16 VMIs of the Gammex-467 phantom.

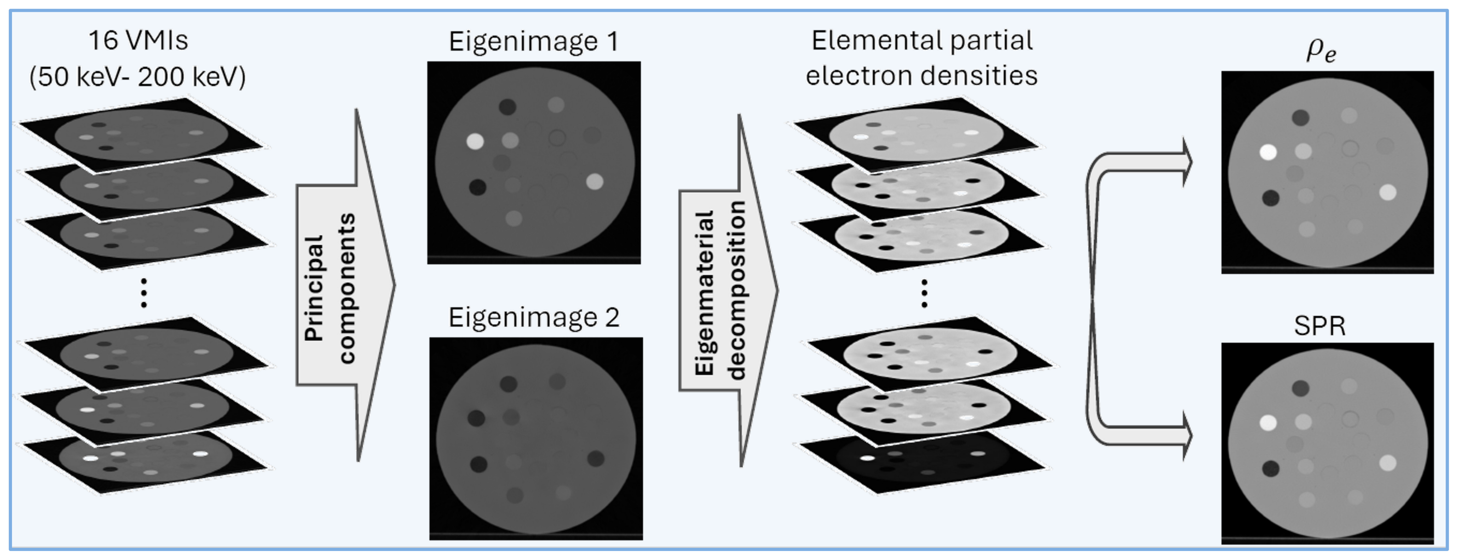

Figure 4. Workflow of the proposed PCA-based framework for estimating electron density relative to water (ρ_e) and proton stopping power ratio (SPR) from DECT VMIs.

RESULTS

PCA demonstrated that the VMI dataset is highly redundant. The first two principal components explained approximately 99.5% of the total variance, confirming that nearly all relevant information can be represented by two eigenimages.

Application of the eigenmaterial decomposition (EMD) framework to the PCA-derived eigenimages produced accurate estimates of ρ_e and SPR across the 13 tissue-equivalent inserts of the Gammex-467 phantom. The estimated values exhibited good agreement with reference data and small systematic biases.

The proposed method achieved the lowest errors among all approaches evaluated. RMS errors in ρ_e are 0.94% for the eigenimages, compared with 1.08% for the 50/200 keV VMI pair and 1.36% for scanner-derived maps. RMS errors in SPR are 1.02%, 1.19%, and 2.45%, respectively.

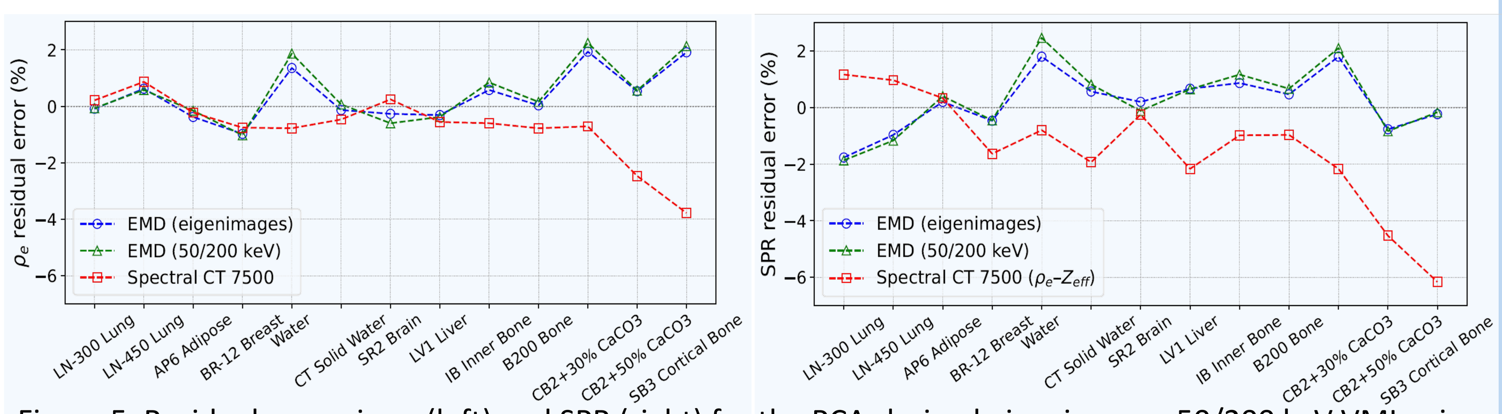

Figure 5. Residual errors in ρ_e (left) and SPR (right) for the PCA-derived eigenimages, 50/200 keV VMI pair, and scanner-derived estimates.

Table 1. Means and RMS errors (%) in ρ_e and SPR for the PCA-derived eigenimages, 50/200 keV VMI pair, and scanner-derived estimates.

Method	ρ_e		SPR	
	RMS	Mean	RMS	Mean
EMD (eigenimages 1,2)	0.94	0.37	1.02	0.17
EMD (50/200 keV)	1.08	0.48	1.19	0.28
Philips Spectral CT 7500	1.36	-0.75	2.45	-1.43

DISCUSSION

The VMI dataset generated by dual-energy CT is highly redundant because all VMIs are reconstructed from the same underlying spectral acquisition. This redundancy is confirmed by PCA, which showed that the first two principal components captured approximately 99.5% of the total variance in the phantom dataset. Therefore, nearly all relevant spectral information can be represented using only two independent component images.

Unlike conventional approaches that rely on a predefined VMI pair, the proposed method combines information from all available VMIs in a data-driven manner. The resulting eigenimages provide optimized inputs for quantitative tissue characterization by preserving the dominant information while reducing redundancy.

The more accurate estimation observed for both ρ_e and SPR suggests that PCA-derived eigenimages better exploit the information embedded in the reconstructed VMI dataset. The reduction in SPR RMS error from 1.19% for the 50/200 keV VMI pair to 1.02% for the eigenimages, and from 2.45% for scanner-derived estimates, demonstrates the potential of this approach for improving quantitative DECT-based proton treatment planning.

Because the proposed method operates entirely in the image domain and requires only post-processing of the reconstructed VMIs, it can be implemented without modifications to scanner acquisition or reconstruction pipelines.

CONCLUSIONS

PCA-derived eigenimages provide an effective and practical approach for exploiting the spectral information available in dual-energy CT. Experiments with a tissue characterization phantom showed improved estimation of electron density and proton stopping power ratio compared with both conventional VMI-based and scanner-derived methods. The proposed image-domain framework enables improved quantitative tissue characterization for proton therapy applications.

REFERENCES

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CONTACT

Prof. Hugo Bouchard

Department of Physics, Université de Montréal, Montréal, QC, Canada

h.bouchard@umontreal.ca