Guest Editorial
Special Issue on Spectral CT

SINCE Hounsfield's Nobel Prize winning breakthrough decades ago, X-ray CT has been widely applied in biomedical applications, producing a huge number of tomographic gray-scale images. However, these images are often insufficient to reveal soft tissue differences and fail to meet many clinical and preclinical needs. The common X-ray tube has a polychromatic spectrum, and it has been desirable and now feasible to obtain spectral or multi-energy CT images with advanced technologies especially energy-discriminating photon-counting detectors. The photon-counting technology is ideal for material decomposition including K-edge imaging, and promises significantly better diagnostic performance than current dual-energy CT techniques. With the rapid development of the photon-counting technology, spectral CT with photon-counting detectors represents a paradigm shift in the CT field.

This special issue serves as a forum of high visibility and synergy to promote the momentum of spectral CT. Through a rigorous peer-review process, 14 high-quality papers[1] have been included from leading groups around the world. These papers give a panorama of the state of the art, addressing challenges in detector and source technologies, image reconstruction, material decomposition, performance evaluation, biomedical, and other applications.

Panta *et al.* [2] suggest an automatic technique for calibrating the energy response of a spectral X-ray detector Medipix3RX with kVp being stepped through a range of interest. Also, they propose a technique for calibrating the energy response using X-ray fluorescence generated by metallic targets irradiated with polychromatic X-rays and gamma-rays. These techniques are demonstrated as practical quality control tools. Hamann *et al.* [3] evaluate the performance of a Medipix3RX detector. High resistivity gallium arsenide is a suitable sensor material for spectral imaging up to 60 keV. In the cases of small pixel sizes, charge sharing compromises the imaging performance and can be corrected with a charge summing circuit. They characterize the Medipix3RX detector assembly with a 500-μm-thick chromium compensated gallium arsenide sensor. Li *et al.* [4] promote the scheme of hybrid detectors that combine the dynamic-threshold-based counting and integrating modes. With their scheme, the number of energy bins can be retrospectively specified, even in a spatially varying fashion. Also, they develop a tensor-based PRISM algorithm to reconstruct a spectral CT image from dynamic dual-energy datasets.

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[1]Due to a clerical error, the paper by Long and Fessler [1] was published in a regular issue earlier.

Hsieh and Pelc [5] design a dynamic attenuator to address the limited characteristic count rate of the photon-counting detector. This basic idea was proposed in their previous paper but they did not explore the impact on spectral applications. In the current paper, they estimate the Cramer-Rao lower bound of the variance of material selective and equivalent mono-energetic images. It is found that rare earth elements, such as erbium, outperform the previously proposed materials such as iron in spectral imaging. The imaging performance with the dynamic attenuator can be an order of magnitude better than that with the conventional static bowtie. Ouyang *et al.* [6] analyze a spectral CT system consisting of an X-ray source and multiple K-edge filters proximal to the X-ray tube. By performing simultaneous reconstructions in associated energy bins, they show consistence between experimental and numerical data with a reasonably complex phantom. The five balanced K-edge filters include Molybdenum, Cerium, Dysprosium, Erbium, and Tungsten, respectively. The proposed system design is cost-effective at clinically relevant fluxes.

Kim *et al.* [7] develop a penalized maximum likelihood algorithm for kVp-switching-driven spectral CT. Their cost function consists of the Poisson log-likelihood for X-ray transmission and a non-convex spectral patch-based low-rank penalty. Given a relatively small number of materials within a patch, a low-rank penalty is insensitive to intensity change while preserving edge information. The separable quadratic surrogate and concave convex procedure are used for optimization on GPU. Zhao *et al.* [8] formulate the dual-energy data acquisition process, and extend the classic ART method to solve the nonlinear system. The method does not require consistent rays with different X-ray spectra. Also, the method has a high degree of parallelism. Xi *et al.* [9] utilize the structural correlation among images in different energy bins and propose two iterative reconstruction algorithms. The constraint for the first algorithm is a well-reconstructed broad-spectrum image, and for the other algorithm is a pseudo narrow-energy image estimated via structural coupling. The structural coupling method links images reconstructed respectively from broad-spectrum and narrow-energy-bin CT datasets, outperforming conventional iterative algorithms. Long and Fessler [1] propose a penalized-likelihood algorithm with edge-preserving regularization for material decomposition. They use an optimization transfer method with a series of pixel-wise separable quadratic surrogate functions to reduce the complicated cost function monotonically. Their algorithm separates pixels for simultaneous update faster than their previously proposed algorithms, reducing noise, streaks, and cross-talks.

Yveborg *et al.* [10] suggest a scheme to maximize the Hotelling-SDNR for spectral X-ray radiography. In their work, frequency-dependent weights are optimized for a multi-bin system. As a result, the detectability is significantly improved in a realistic simulation study for high frequency objects based on a simplified model of a silicon detector. Bornefalk *et al.* [11] focus on material decomposition in the sinogram domain with an emphasis on the effect of a spectral CT forward model mismatch. They determine the maximum allowed forward model error so that quantification error is still defined by statistical uncertainty. Assuming a silicon-detector, they conclude that the bin edges need to be known within 0.15 keV for quantum-limited material decomposition. Yveborg *et al.* [12] theoretically compare dual-energy CT and silicon-detector-based spectral CT for material quantification. The noise levels of contrast agent quantification using the proposed silicon detector are higher than those with dual-energy CT if the composition of an object is known. However, dual energy CT is subject to model mismatch and large bias in contrast agent quantification.

Mendonca *et al.* [13] characterize liver fibrosis using dual-energy CT. By combining a material decomposition method with a biologically driven hypothesis, they analyze datasets from 12 patients, and show the spatial distributions of liver fibrosis in terms of scoring and correlation with severity of fibrosis across disease severities. The data are in agreement with MRE in a patient with severe fibrosis. Also, a longitudinal study of the cohort gives repeatable results. Epple *et al.* [14] investigate a combination of spectral CT and grating-based phase-contrast imaging. The polychromatic spectrum traditionally compromises the performance of grating-based X-ray imaging but a benefit is obtained with a photon-counting detector. They measure phase shifts in various energy bins to estimate the most likely phase shift, suppress phase-wrapping artifacts, and improve the contrast-to-noise ratio.

While we are proud of this special issue for its wide coverage and high quality of reported research, taking this opportunity we would like to underline that these cutting-edge results seem only a glimpse into the huge potential of spectral CT. Current molecular imaging modalities, especially PET, SPECT, MRI, and optical imaging, have gone a long way towards peeking into biological processes at the molecular and cellular levels, but they are still far from capturing the whole picture. PET and SPECT, although sensitive, are slow, nonspecific, and require radioactive tracers. MRI has great soft tissue contrast (proton density, T1, T2, flow, chemical shift, elasticity, and temperature) but long imaging time for high spatial resolution, and it cannot be used for patients with claustrophobia, pacemakers, or aneurysm clips. While metabolites have characteristic peaks of involved nuclei, MRI is often not highly quantitative for complex or dynamic features of the body. Optical molecular tomography is sensitive and specific but its limited penetration depth prevents its use for most clinical tasks. Now, with chemically specific multi-contrast mechanisms, spectral CT promises to complement existing modalities in an unprecedented fashion.

Finally, we are grateful for the guidance from the former and current Editors-in-Chief, the help from the TMI office, and most importantly the tremendous efforts by the authors and the reviewers. Without any of these, it would have been impossible to celebrate such a volume of inspiring papers in the spectral CT field.

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