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Dose-Efficient Energy-Selective Diagnostic Computed Tomography

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Energy-selective computed tomography is a special approach in clinical CT aiming at acquiring energy-resolved information regarding the x-ray attenuation distribution inside a patient. This is useful since the energy-resolved information allows distinguishing and identifying different materials and tissue types in the patient. Especially the visualization of the distribution of oral or intravenous contrast agents and their quantification is of interest. Some of today's clinical CT scanners are dual energy-capable, meaning that they acquire projection data of the patient at two different effective energies. A typical clinical dual energy application is virtual non-contrast imaging and imaging of the iodinated contrast agent. The aim of virtual non-contrast imaging is to artificially remove the contrast enhancement due to the contrast agent application to obtain an image that closely resembles a native scan of the patient without any contrast agent. This might save the native scan and thus patient dose.

There are different technical realizations of dual energy CT in the clinics. In this work, a simulation study was carried out to compare the material decomposition performance of the different dual energy techniques in virtual non-contrast and iodine imaging by means of the material image quality. The best performance was found for dual source dual energy CT, which employs two source-detector pairs on the rotating gantry, allowing to independently set the tube voltages and pre-filtering for the two x-ray tubes. The second best performance was achieved by subsequent scanning of the patient with two different x-ray spectra, but this approach has disadvantages regarding patient motion and temporal changes of the contrast agent distribution. The third best performance could be attributed to fast kV switching, which rapidly changes the tube voltage from projection to projection. While this approach acquires the successive low and high energy projections nearly simultaneously, it currently does not allow to freely adjust the dose ratio for the projections at the two energies, which may lead to suboptimal results in a material decomposition. The fourth best performance was found for the sandwich detector technique. This technique is using a detector consisting of two detector layers, where the upper layer detects the low energy part and the lower detector layer the high energy part of the x-ray spectrum. This approach suffers from the spectral overlap between the two detected energy information.

A new kind of detector technology is emerging in the field of medical imaging, the so-called photon counting detectors. These detectors directly allow to measure the incident x-ray spectrum in an energy-resolved manner and to count the incident x-ray photons into predefined energy bins. Employing such detectors enables not only dual energy CT, but even multi energy CT. The classical dual energy applications require, however, only two energy bins. The additionally available energy information should be used and not just be averaged or discarded. To allow this, a statistical image-based material decomposition algorithm was developed in this work that is using the additional energy information to improve the material image quality. Simulating an ideal photon counting detector with different numbers of energy bins in the virtual non-contrast and iodine imaging scenario shows a great patient dose saving potential, which increases with increasing number of energy bins at a constant patient dose. While these results for an ideal photon counting detector are very promising, in reality photon counting detectors suffer from different effects leading to wrong classifications of photon energies and thus of overlapping energy bins. Using a more realistic photon counting detector model from the literature in the simulations showed a significantly decreased performance even with many energy bins compared to an ideal detector. The performance of a realistic photon counting detector is only at the level of today's clinical dual energy CT. These results predict currently no great gain for clinical dual energy CT from photon counting detectors. The developed image-based material decomposition algorithm was shown to efficiently make use of additionally available energy information, which helps to improve the image quality of material images from photon counting detectors. The achievable improvements of the developed statistical image-based material decomposition algorithm were compared to results obtained with a maximum likelihood projection-based material decomposition algorithm from the literature, finding a good agreement and ensuring statistically optimal results.

The results obtained with the more realistic photon counting detector model from the literature already indicated the need for a realistic photon counting detector model to be able to realistically assess the performance to be expected from such detectors. The model from the literature did not provide the means to describe the processes occurring in the photon counting detector and the resulting correlations between the energy bins of neighboring detector pixels. This is possible with very extensive and slow Monte Carlo simulations, but a simpler and faster approach for simulations with correct statistics was sought. Therefore, a concept based on describing the energy bin counter increase patterns on the detector resulting from different types of photon interactions with the detector was developed and found to be consistent to other models and measurement results from the literature. Different evaluations of the simulation results obtained with the developed photon counting detector model showed that the occurring correlations are not of great importance in image-based material decomposition. Accurate performance results for photon counting detectors can also be obtained by simpler detector models, as long as the spectral response of the detector is correctly modeled, respecting the fact that a single x-ray photon can increase more than just one counter. However, to obtain such realistic spectral response functions, a realistic modeling of the processes in the photon counting detector, as in the developed model, is required. Measuring the spectral response of a photon counting detector is also possible, but a problem in measurements is that the incident number of photons, which is required to obtain the correct scaling, may be difficult to determine. The photon counting detector technology is still under development and improvements by different techniques to compensate for the detrimental effects are to be expected in the near future, making this technology interesting for clinical applications.