Empirical Cupping Correction for CT Scanners with Primary Modulation (ECCP)

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Purpose: X-ray CT measures the attenuation of polychromatic x-rays through an object. The rawdata acquired, which are the negative logarithm of the relative x-ray intensity behind the patient, must undergo water precorrection to linearize the measurement and to convert them into line integrals that are ready for reconstruction. The function to linearize the measured projection data depends on the detected spectrum of the ray. This spectrum may vary as a function of the detector position, e.g. in cases where the heel effect becomes relevant, or where a bow-tie filter introduces channel-dependent beam hardening, or in cases where a primary modulator [1] is used to modulate the primary intensity of the spectrum.

Method and Materials: To solve this problem we propose an extension of the ECC [2] idea. Let u and v denote the position on the detector and α denote the projection angle that defines the source position. $M(\alpha, u, v)$ reflects the modulation of the intensities induced by the primary modulator. Up to a scaling factor, $M(\alpha, u, v)$ can be thought to be a value between 0 and 1. Based on this and the ECC idea the general scheme of the ECCP is shown in figure 1. The thus determined coefficients c_{ij} are then stored and used for the precorrection of subsequent CT scans with arbitrary objects.

For the calibration of the ECCP a phantom mainly consisting of one known material has to be used. We used a water phantom and the corresponding basis images $f_{ij}(\mathbf{r})$ are shown in figure 2.

For the evaluation of the proposed method we used a flat-panel tabletop cone-beam CT system [1]. For the primary modulation a 0.210 mm thick copper modulator with a checker-board pattern has been used. The pattern size of the modulator corresponds to about 11 detector pixels (figure 3).

Results: For the first experiment we used the cylindrical water phantom which is also our calibration phantom. Three reconstructions were carried out and are presented in figure 4. The severe ring artifacts introduced by the modulator are eliminated by the proposed ECCP method. This finding is validated by the more quantitative view at profile plots shown in figure 5.

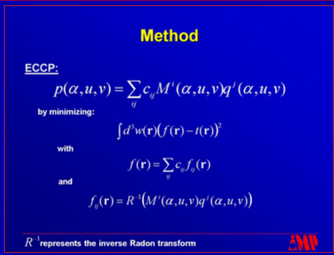

Figure 1: General scheme of the ECCP.

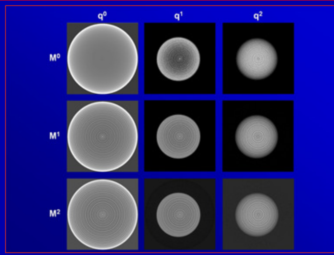

Figure 2: Basis images of the water phantom used for ECCP calibration. The basis images are shown up to the quadratic terms. All images are scaled to have the windowing centered around the mean value and the window width is four times the standard deviation.

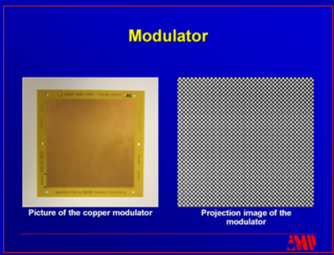

Figure 3: Photograph and projection image of the modulator.

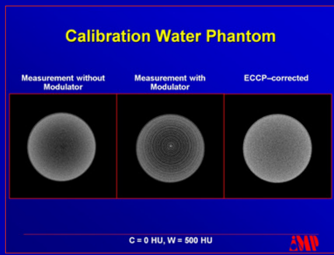

Figure 4: Reconstructions of the water phantom. The figure shows the reconstructions from a conventional measurement (no primary modulator), from a measurement with the modulator in place, and from the same measurement reconstructed with ECCP.

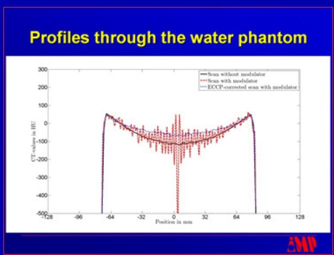

Figure 5: Figure shows the plots through the different reconstructions of the water phantom.

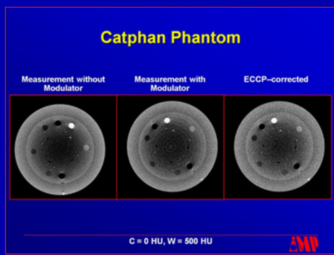

Figure 6: Reconstructions of the Catphan phantom. Reconstructions from a conventional measurement, from a primary modulator measurement and its ECCP-corrected version are presented.

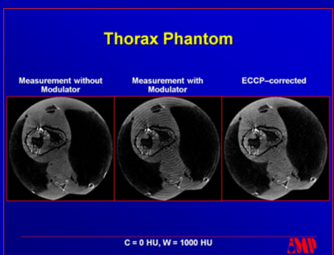

Figure 7: Reconstructions of the anthropomorphic thorax phantom. Transaxial slices are shown for the three cases: measurement without modulator, measurement with modulator without ECCP and measurement with modulator and with ECCP correction.

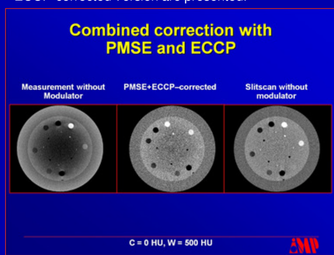

Figure 8: Reconstructions of a standard measurement, of the PMSE and ECCP-corrected measurement with modulator, and of a slitscan.

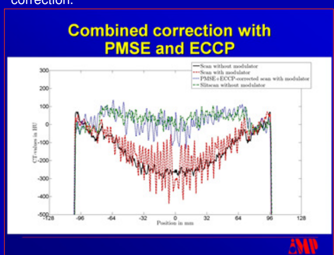

Figure 9: Profiles through the different reconstructions of the Catphan phantom, including the reconstruction of the measurement with modulator but without PMSE and ECCP

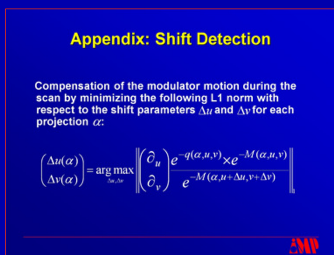

Figure 10: Cost function for the motion compensation.

As a second test we applied the ECCP coefficients determined from the water phantom data to the Catphan phantom scan (figure 6). Obviously, ECCP is able to remove the ring artifacts induced by the primary modulator's beam hardening. The increased noise in the measurement with modulator is based on the fact that all measurements are made with the same scan parameters and the installed modulator leads to a reduced primary intensity.

Our third test applies the ECCP to an anthropomorphic thorax phantom. To correct the data for the effects of the primary modulation the ECCP coefficients determined from the water phantom measurements were used. Figure 7 shows that the artifacts introduced by the modulator were almost completely removed by ECCP.

As a final experiment we combined the primary modulator scatter estimation [1] (PMSE) with ECCP. To do so, new ECCP correction coefficients were determined from the water phantom measurement. In contrast to the previous tests we now apply PMSE to the water phantom rawdata prior to running the ECCP calibration. These new ECCP coefficients were then used to correct the PMSE-corrected projection data of the Catphan phantom. Figure 8 shows the corresponding reconstructions. Obviously, PMSE and ECCP work together quite well. Ring artifacts, beam hardening artifacts and cupping due to scatter are nearly completely removed. Comparison with the slitscan image reveals that some real slight scatter artifacts remain. These findings are confirmed by the profile plots shown in figure 9.

Conclusion: The empirical cupping correction for primary modulation (ECCP) provides precorrection for spatially varying spectral properties of the x-rays, as they may be induced by a spatially varying pre- or post-filtration. The development of ECCP was motivated by the primary beam modulator that is part of the PMSE method used to suppress scatter artifacts. However, ECCP is likely to be useful in other situations as well. These may include, but are not limited to, the use of ECCP to compensate for shaped prefiltration, for the heel effect, or for scratches in the pre- or post filtration that induce subtle ring artifacts in the reconstructed CT images.

[1] H. Gao, Med. Phys., vol. 37, pp. 934 - 946, Feb 2010.
[2] M. Kachelrieß et al., Med. Phys., vol. 33, pp. 1269 -1274, 2006

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MIC 2011