

Hybrid Scatter Correction for CT Imaging

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Purpose:

The purpose of this study was to develop and evaluate the hybrid scatter correction algorithm (HSC) for CT imaging. Therefore two established ways to perform scatter correction, physical scatter correction based on Monte Carlo simulations and convolution-based scatter correction, were combined in order to perform an object-dependent, fast and accurate scatter removal.

Based on a reconstructed CT volume, patient-specific scatter intensity is estimated by a coarse Monte Carlo simulation that uses a reduced amount of simulated photons in order to reduce simulation time. To further speed-up the Monte Carlo scatter estimation, scatter intensities are simulated only for a fraction of all projections. In a second step the high noise estimate of the scatter intensity is used to calibrate the open parameters in a convolution-based algorithm which is then used to correct measured intensities for scatter. Further the scatter-corrected intensities are used to reconstruct a scatter-corrected CT volume.

Materials and Methods:

Monte Carlo-based scatter correction is considered to be very accurate since the real physics of photon transport are incorporated in the model. However, currently clinical applicability is hindered by the high computational complexity of the Monte Carlo scatter reduction methods.

Convolution-based scatter correction on the other hand has far less computational needs since scatter intensity is estimated by scaling and low-pass filtering measured intensities. Their drawback is that the semi empirical models used have open parameters which must be calibrated in advance based on reference objects which also causes them to be not patient-specific.

With HSC the Monte Carlo simulation is accelerated by reducing the number of simulated photons and by reducing the number of projections for which the Monte Carlo simulation is done. This reduced number of photon histories comes at the cost of a higher noise level in the scatter estimate. Therefore instead of using the high

Monte Carlo-Based Scatter Estimation

- With Monte Carlo simulations the physical path of photons through the object is simulated. Therefore Monte Carlo simulation is considered to be very accurate in terms of scatter estimation.
- The physical effects which play a role in kV CT imaging are Compton scatter, photo effect, and Rayleigh scatter. Photon paths are simulated by randomly sampling from cross section data and probability density functions of scatter angles.
- Many photon paths must be simulated in order to generate low noise scatter signals. This results in a higher computational complexity as compared to convolution-based methods [2].

Convolution-Based Scatter Estimation

- Convolution-based scatter estimation is based on the low frequency nature of scatter intensities.
- The scatter intensity I_s is estimated by scaling measured intensities I_m or attenuations μ_m with the scatter potential Φ followed by a convolution with the scatter kernel K .
- In our hybrid scatter correction we used the convolution-based model of Ohnesorge et al. [1] to generate an estimate I_{sc} of the real scatter intensity I_s .

$$\Phi(\beta, \gamma, \epsilon_1, \epsilon_2, \epsilon_3) = \epsilon_1 + \epsilon_2 \cdot \epsilon_3 \cdot \epsilon_4$$

$$K(\beta, \gamma, \epsilon_1, \epsilon_2, \epsilon_3, \epsilon_4) = \sum_{i=1}^N e^{-\alpha_i \beta + \epsilon_1 \epsilon_2 \epsilon_3} \cdot \sum_{j=1}^M e^{-\alpha_j \gamma + \epsilon_1 \epsilon_2 \epsilon_3}$$

$$I_{sc}^{(2D)}(\beta, \gamma, \epsilon) = \Phi(\beta, \gamma, \epsilon_1, \epsilon_2, \epsilon_3) \cdot K(\beta, \gamma, \epsilon_1, \epsilon_2, \epsilon_3)$$

$$I_{sc} = \mu_m \otimes K(\beta, \gamma, \epsilon) + \epsilon_4 \cdot \mu_m$$

- The open coefficients $\alpha_i, \alpha_j, \epsilon_4$ must be determined prior to scatter correction. In the original publication [reference [1]] they were determined by calibration measurements. We here propose to calibrate the coefficients with a Monte Carlo estimate of the scatter intensity.

Hybrid Scatter Correction

- The hybrid scatter correction combines convolution-based with Monte Carlo-based scatter estimation in order to do a fast, accurate, and object-dependent scatter correction.
- Based on an initial reconstruction a Monte Carlo scatter simulation is performed in order to generate an estimate of the scatter intensity.
- To reduce the computation time of the Monte Carlo simulations the number of simulated Monte Carlo photons is reduced.
- The reduced number of photons comes at the cost of a higher noise level in the scatter signal.
- This is overcome by using the high noise Monte Carlo signal not directly but to calibrate the open coefficients in the convolution-based model.

$$e(\alpha) = \arg \min_{\alpha} \int d\beta d\gamma (I_{sc}^{(2D)}(\alpha, \beta, \gamma) - I_{sc}^{(2D)}(\alpha, \beta, \gamma, e))^2$$

$$I_{sc}^{(2D)}, I_{sc}^{(3D)}: \text{Convolution- and Monte Carlo-based estimates of the scatter intensity}$$

- The calibrated convolution-based method is used for scatter correction.

Evaluation

- In a monoenergetic simulation study we first determined the number of photons N_{MC} in the Monte Carlo simulation step of HSC and the number N_{ref} of projections for which the coefficients α are recalibrated.
- Calibration angles were equally spaced over 360° in 15° steps. The calibration steps were computed by linear interpolation.
- We then used the results for N_{MC} and N_{ref} to determine the scatter reduction potential of HSC in the polychromatic simulation study and for measured data.
- As a measure of scatter reduction potential we computed the error between the scatter-corrected and the scatter-free reference image.

$$E = \sqrt{\frac{\int d\alpha (I_{sc}(\alpha) - I(r))^2}{\int d\alpha (I_{sc}(\alpha) + I(r))^2}}$$

Number of Photons and Calibrations

- Upper figure: The dependency of the error in the scatter-corrected image on the number of simulated Monte Carlo photons is depicted. Up to a relative photon number of 0.01 only a minor increase in the error can be observed. Here N_{ref} is the number of photons used in a low noise reference Monte Carlo simulation.
- Lower figure: The dependency of the error in the scatter-corrected image was investigated as a function of the number of calibration steps used to calibrate a new parameter set for the convolution-based model. If the calibration is done for more than 16 projections, distributed equally spaced over a full rotation, only minor changes in the error can be observed.

	Image (Simulation)	Diff to Reference (Simulation)	Image (Measurement)	Diff to Reference (Measurement)
Reference				
Uncorrected				
HSC-scatter-corrected				
HSC-scatter+ BH-corrected				

Results for the scatter correction potential of HSC in case of polychromatic data. For the simulations the reference image is a beam hardening-corrected image reconstructed from primary radiation only. For the measurements the reference is corrected for scatter with a low noise Monte Carlo simulation. On top of the scatter correction a beam hardening correction (EBHC, reference [4]) is performed.

noise estimate directly, we aim at using it only for the determination of the open parameters in the convolution-based algorithm which is then used for scatter correction.

We evaluated the scatter correction potential of HSC in simulations and measurements. For the simulation study we simulated primary and scatter intensities for the Forbild thorax phantom.

Measurements were done for a head phantom on the Varian OBI CBCT scanner (Varian Medical Systems, Palo Alto, USA).

In both cases we applied the empirical cupping correction (ECC) algorithm [3] and the empirical beam hardening correction (EBHC) algorithm [4] to correct for artifacts caused by the polychromatic x-ray spectrum.

Results:

Using our hybrid approach for scatter correction the number of Monte Carlo photons may be reduced by a factor of 50 to 100 as compared to a pure Monte Carlo simulation while still achieving accurate results for the scatter correction. Further, it turned out to be sufficient to recalibrate the parameters of the convolution-based model at an angular increment of 22.5° , i.e. to do the calibration only for 16 projections equally spaced over 360° .

Conclusion:

HSC allows to do a Monte Carlo-based, object-dependent scatter correction with highly reduced computational needs as compared to pure Monte Carlo-based scatter correction while still achieving a good scatter artifact correction.

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