ClearRay reconstruction

Scatter and beam hardening correction

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In recent years, significant advancements have been made in computed tomography (CT) technology and applications. With improvements in the performance of the imaging chain and increased longitudinal (Z-axis) coverage, effects of certain physical factors influencing clinical usage such as scattered radiation has become more apparent. Scattered radiation primarily originates from the scanned object, when the signal deviates from the true measurement of primary X-ray intensity and could result in artifacts, inaccuracy in reconstructed CT attenuation (HU) measurements, and degradation of low contrast resolution within an image.

Traditionally, most MDCT systems employ a post collimation anti-scatter grid (ASG) in the angular (X) direction to compensate for the scatter radiation. However, with increasing Z-axis coverage offered by advanced state-of-the-art multi-slice CT (MSCT) scanners, the scatter level increases significantly and there is an opportunity to use software algorithms to further decrease the impact of scattered radiation. This paper highlights changes to the imaging chain in terms of new scatter and beam hardening correction techniques. These new techniques are based in first principles computations of these corrections and are enabled by advanced ray-tracing and Monte Carlo simulation techniques.

I. Background

The increasing Z-axis coverage in latest generation of MDCT scanners requires larger cone angles for X-rays to ensure an increased field of view. This increasing cone angle increases the scatter radiation along the Z-axis direction. Scattering is the dominant, most probable, way that diagnostic X-rays interact with human tissue. Scatter radiation helps the creation of different grey scales values in CT images and also one of the primary contributors to image quality degradation when it reaches the detector. This amount of scattered radiation that reaches detectors grows with increasing Z-axis coverage of the scanner. As the amount of scattered radiation has been growing continuously, the scatter rejection technology (1-dimensional anti-scatter grids) has barely undergone any improvements in the wide area MDCT scanners. Starting from 64-slice scanners, this scatter radiation results in large scale inhomogeneities in CT attenuation (HU) values as well as dark streaks between strongly absorbing objects[1] in an image as shown in figure 1. Several methods have been investigated to reduce the scatter effect in cone-beam CT including hardware and software solutions. The influence of scatter radiation increases rapidly with coverage and therefore the latest generation of Philips CT scanners, Brilliance iCT with 8 cm Z-axis coverage is equipped with a ClearRay collimator (2D anti-scatter grid) that reduces the affects of scatter in the Z-direction. In an effort to continue with innovations to reduce scatter and improve image quality, Philips CT recently introduced another member in the ClearRay family, ClearRay reconstruction for 64-slice scanners. The purpose of this paper is to describe ClearRay reconstruction that includes improvements to scatter and beam hardening corrections. These improvements are performed view-by-view, detector-by-detector based on individual patient shape and attenuation profile.

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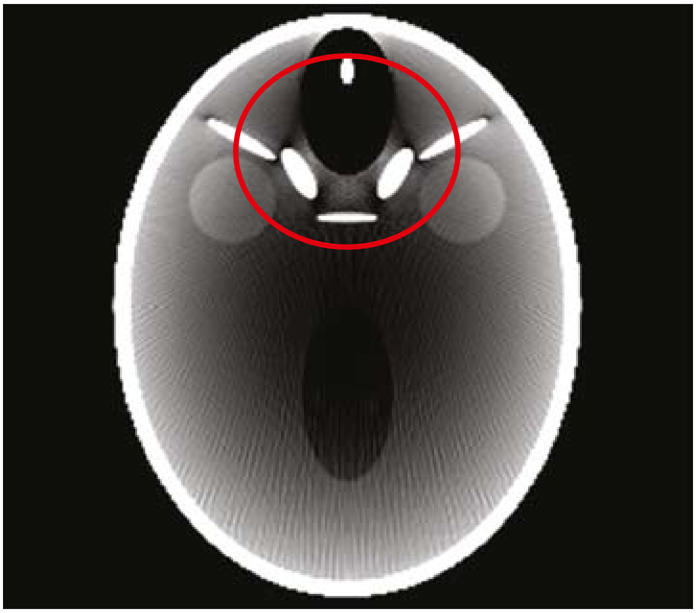

Figure 1. Examples of artifacts caused by scattered radiation. There is an overall cupping that depresses CT levels toward the center of the phantom as well as dark streaks between highly absorbing material.

II. Scatter and beam hardening correction

ClearRay reconstruction embodies a completely new approach to two image correction algorithms: beam hardening and scatter. While beam hardening and scatter correction algorithms are a part of most CT scanners' reconstruction, ClearRay reconstruction represents new innovations that enable the determination of these corrections from first principles employing beam path tracing and Monte Carlo simulations.

Beam hardening is a bias that is introduced in CT due to the variation in the measured patient attenuation caused by the broad polychromatic X-ray spectrum. A mono-energetic X-ray spectrum, if existed practically, would require no beam hardening correction. The goal of a beam hardening correction is then to correct the measurement so that it is as if it came from a system with a mono-energetic X-ray tube spectrum.[2]

Traditional beam hardening corrections rely on physical measurements of the beam hardening effect and a phenomenological correction to the data. These physical measurements are made on particular phantoms and necessarily include other effects such as scatter and off-focal radiation, and must be repeated for each configuration of the scanner.

The innovation introduced by ClearRay reconstruction is to use correction curves that are derived entirely from theoretical calculations of beam hardening. This is enabled by detailed modeling of X-ray tube spectra and ray-tracing through the system's beam path. This modeling allows a computer simulation of the predicted beam hardening correction that would need to be applied to each detector's measurement in order to achieve the nominal value.

There are around 390,000 calibration constants that are determined in this way from first principles. The correction curve is calculated uniquely for each detector at all of the system's X-ray tube potential settings and is applied to each detector's reading at each angle of the gantry. Since this correction is an ideal beam hardening correction free of other confounding effects, it allows for better and more robust treatment of other corrections like scattered radiation.

The second innovation in ClearRay reconstruction is an entirely new treatment of scatter correction. During the measurement of the X-rays transmitted through the patient, the detector measures some X-rays that, instead of coming directly from the X-ray tube, have scattered somewhere in the patient before being detected as shown in figure 2. This essentially contributes an "extra" signal to the detector which, instead of being due to the passage of X-rays along a line from the detector to the X-ray tube, is contributed to by the surrounding material.[3] While the current 64-slice scanners have techniques that are employed for the rejection of scattered X-rays with anti-scatter grids, further improvements in image quality can be achieved with additional algorithmic corrections. Correction of scattered X-ray is one of most challenging problems in X-ray computed tomography because the correction required by a given detector is due to all of the material in the patient, even that extending beyond the measured region.

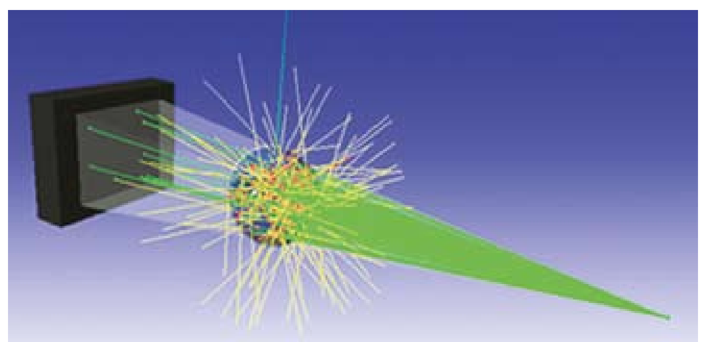

Figure 2. An illustration showing scattered X-rays (yellow lines) from the primary X-rays (green lines). When the scattered X-rays reach the detector they contribute to the reconstructed HU values resulting in non-homogenous HU scale.

Like traditional beam hardening corrections, traditional scatter corrections have been rooted in the tuning of calibration constants based on a relatively small number of measurements on specific phantoms. As such, the corrections are idealized only for these specific phantoms.

The technology enabling the new scatter correction of ClearRay reconstruction is detailed Monte Carlo simulations of the passage of X-rays through patients. Monte Carlo is considered the state-of-the-art technique in computing scatter effects as it essentially simulated the passage of each individual X-ray through the patient.[4] It would be impractical to perform a Monte Carlo computation on each individual patient's scan in real time since it would take around

20 days to perform computations for a single patient. ClearRay reconstruction implements proprietary algorithms to map the attenuation properties of a given patient to a large database of pre-computed Monte Carlo simulations. In this way, advantage is taken of the precision and accuracy of the Monte Carlo technique, while still having a correction that is tailored for each patient. Figures 3a and 3b demonstrate the influence of ClearRay reconstruction on scatter radiation and thereby on CT attenuation (HU) values.

ClearRay reconstruction makes use of a large database of pre-computed beam hardening and scatter corrections. There are hundreds of hours of modeling and simulation computing that is required for each scanner model where ClearRay is available. Since the computational expense has been paid in advance, the overall reconstruction time for images has been preserved.

III. Results

The performance of ClearRay reconstruction was evaluated on a dedicated large scatter phantom, 40 cm in diameter with four rod-shaped Teflon pins. Figure 4 demonstrates images of the scatter phantom without and with ClearRay reconstruction. The results illustrate improved image quality with reduction in dark streaks and the cupping artifacts.

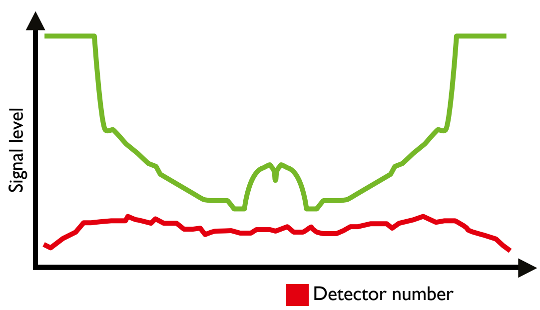

Figure 3a. The green line represents the primary X-ray signal post reconstruction The red line represents the scattered radiation. Since amount scatter radiation is largest at center, CT image artifacts are typically more prominent in the center of the reconstruction.

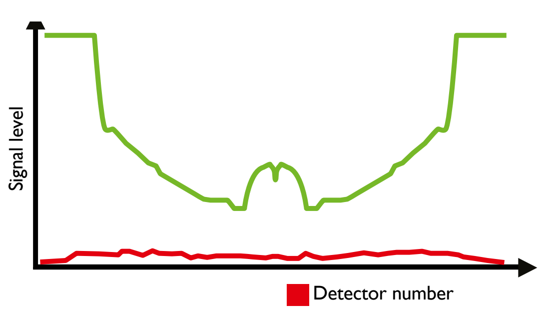

Figure 3b. This image shows the effect of ClearRay reconstruction where it reduces scatter radiation thereby reducing its contribution to the CT attenuation (HU) values making them more uniform.

A preliminary analysis on patient studies showed a significant improvement in the Hounsfield scale across diverse patient sizes. One particular illustration of this is in the evaluation of the level of renal cysts. Figure 5 shows the distribution of renal cysts levels with and without ClearRay reconstruction. There is an overall shift in level as well as a narrowing of the distribution, both of which are direct results of the improved algorithms of ClearRay. The narrowing of the distribution is understood to be due to a normalization of the CT level across different patient sizes. ClearRay reconstruction being rooted in patient adapted scatter and beam hardening corrections, provides more stable readings from small to large patients. In addition to eliminating the inhomogeneity artifacts and fully guaranteeing an absolute Hounsfield scale in arbitrary imaging conditions, the new technique also helps to strongly sharpen object boundaries such as the edges of the liver or the kidney. Since ClearRay reconstruction includes a fully three-dimensional treatment of the propagation of scattered radiation in a patient, it provides a better correction of organ boundaries, as illustrated in figures 6-8.

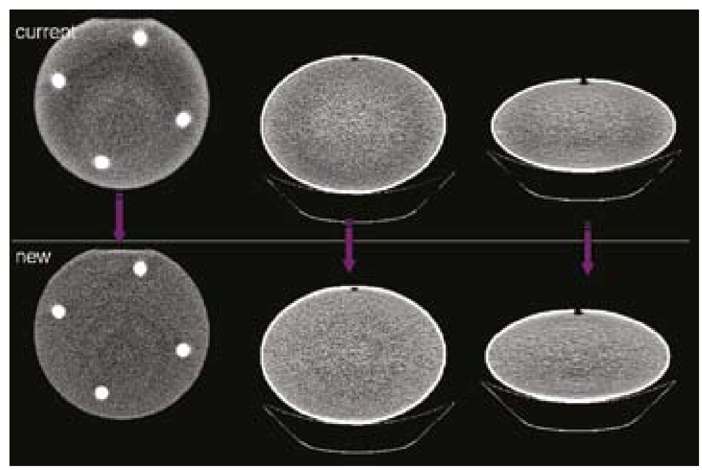

Figure 4. Image quality improvement demonstrated on various water phantoms. The phantom on the left has Teflon pins to simulate the effect of bones. Images in the bottom row demonstrate the effect of ClearRay reconstruction in improving image quality and overall uniformity.

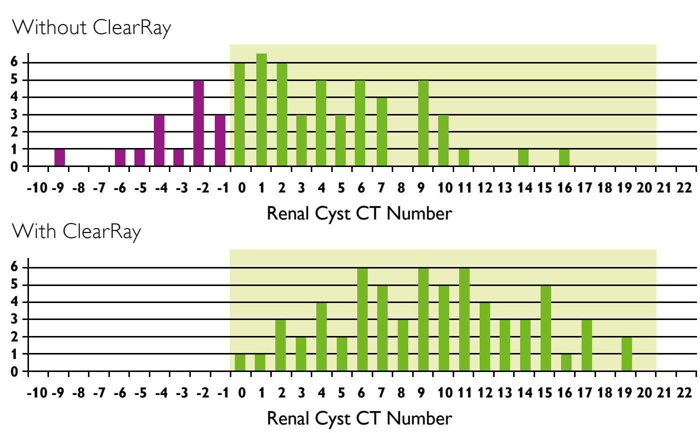

Figure 5. An analysis of the CT level in renal cysts with and without ClearRay. The green area is an annotation of the "Bosniak Criteria" for the differentiation of renal cysts in CT.[5]

Figure 6. The above image demonstrates the increase in sharpness for liver and other abdominal organ boundaries due to ClearRay reconstruction.

Figure 7. ClearRay reconstruction improves the homogeneity of HU values in large organs like the liver. In this case, uniformity of the liver is improved at the top of the liver near the diaphragm. The 3D modeling of scatter built into ClearRay reconstruction accurately corrects scatter near the low density lung field.

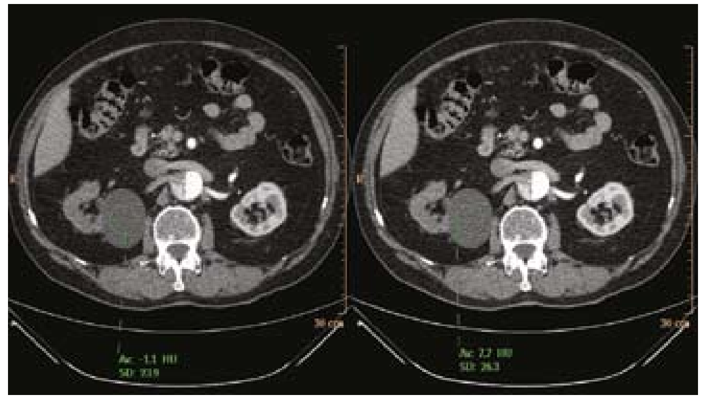

Figure 8. The image on the left is without ClearRay reconstruction and the image on the right is the same patient data analyzed with the new ClearRay reconstruction.

III. Conclusion

ClearRay reconstruction represents revolutionary solutions to beam hardening and scatter artifacts. New modeling and simulation technology allows the beam hardening and scatter corrections to be pre-computed and stored in a database which is consulted to yield a correction that is tailored to each individual patient. As a fully three-dimensional correction, the stability of the contrast scale is preserved across different patient sizes, the uniformity within an image is improved, and organ boundaries are better visualized. This technology enhances image quality and enables wider coverage scanners.

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