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Simultaneous scatter rejection and correction method using 2D antiscatter grids for CBCT

Zhelin Yu^{a,†}, Yeonok Park^{b,†}, Cem Altunbas^{b,*}

^aDepartment of Computer Science and Engineering, University of Colorado Denver, Denver, CO, USA

^bDepartment of Radiation Oncology, University of Colorado School of Medicine, Aurora, CO, USA

Abstract

While two-dimensional antiscatter grids (2D grid) reduce scatter intensity substantially in Cone Beam Computed Tomography (CBCT), a small fraction of scattered radiation is transmitted through the 2D grid to the detector. Residual scatter limits the accuracy of CT numbers and interferes with the correction of grid's septal shadows, or footprint, in projections. If grid's septal shadows are not adequately suppressed in projections, it will lead to ring artifacts in CBCT images. In this work, we present a new method to correct residual scatter transmitted through the grid by employing the 2D grid itself as a residual scatter measurement device.

Our method, referred as grid-based scatter sampling (GSS), exploits the spatial modulation of primary x-ray fluence by 2D grid's septal shadows. The shape of the signal modulation pattern varies as a function of residual scatter intensity registered by detector pixels. Such a variation in signal pattern was employed to measure residual scatter intensity in each projection, and subsequently, residual scatter was subtracted from each projection.

To validate the GSS method, CBCT imaging experiments were conducted using a 2D antiscatter grid prototype in a linac mounted CBCT system. The effect of GSS method on the ring artifact reduction was quantified by measuring noise in CBCT images. In addition, the nonuniformity of Hounsfield Units (HU) and HU accuracy was measured in both head and pelvis-sized phantoms.

In qualitative evaluations, GSS method successfully reduced ring artifacts caused by 2D grid's footprint. Image noise reduced by 23% due to reduction of ring artifacts. HU nonuniformity in water-equivalent sections was reduced from 20 HU to 10 HU, and streak artifacts between high density inserts were reduced. The phantom size dependent variations in HU was also reduced after application of GSS method. Without GSS method, HU of density inserts reduced by 9% on the average when phantom size was increased from head to pelvis. With GSS method, HU values reduced only by 5% under the same conditions.

In summary, GSS method complements the 2D grid's scatter suppression performance, by correcting the scatter transmitted through the grid. This approach does not require additional scatter-measurement hardware, such as beam-stop arrays, since the grid itself is employed as the scatter measurement device. By suppressing residual scatter in projections, our proposed method

* cem.altunbas@cuanschutz.edu.

† First co-authors

successfully reduced artifacts caused by 2D grid's footprint, and further improved CT number accuracy.

Keywords

antiscatter grid; scatter correction; CBCT; flat panel detectors

1. INTRODUCTION

Scattered radiation is one of the fundamental problems in CBCT that degrades both CT number accuracy and contrast-to-noise ratio (CNR). Recently introduced 2D antiscatter grids aim to address this problem, by providing significantly better scatter suppression performance than radiographic antiscatter grids[1–3]. While 2D grids improve CT number accuracy and CNR, a small fraction of scatter fluence, referred as residual scatter, is transmitted through the 2D grid to the x-ray detector. For example, during imaging of pelvis-sized objects, scatter-to-primary ratio (SPR) can be in the order of 0.2–0.3 in projections (Fig. 1(a)) [2]. While such a SPR is relatively small, residual scatter still degrades the accuracy of CT numbers and leads to suboptimal suppression of 2D grid's septal shadows in projections.

The latter issue is particularly important in achieving artifact-free images with 2D grids; if 2D grid's septal shadows are not suppressed sufficiently in projections, they will lead to ring artifacts in CBCT images (Fig. 1(b)). This problem is partly related to the flat field (or gain map) correction process used in flat panel detectors; gain map correction does not effectively suppress the grid's septal shadows in the presence of residual scatter. This effect was explained in more detail in Sec. 2. Similar issues were also observed with conventional 1D antiscatter grids used in fluoroscopy [4].

To suppress residual scatter and address the above-mentioned problems, we developed a new method, where 2D grid itself is used as a scatter measurement device. Briefly, in our approach, 2D grid's septa act as a micro array of beam-stops placed on the detector; septal shadows reduce the primary intensity in detector pixels underneath grid's septa. On the other hand, scatter signal is minimally affected by grid's septal shadows. In our method, we exploit the spatial varying primary signal due to grid septa and spatially uniform nature of scatter signal, to measure residual scatter intensity. Once residual scatter is measured, it subtracted from the projections to obtain primary-only projections. Our approach is referred as Grid based Scatter Sampling (GSS) Method in the rest of text.

2. MATERIALS AND METHODS

2.1 Formation of grid artifacts in projections

First, we will describe the Gain Map, or Flat Field, correction method, which is commonly used to minimize pixel to pixel sensitivity variations in x-ray detectors[5, 6]. A Gain Map (GM) is a 2D array of pixel specific normalization factors obtained from a flood projection (no object in the x-ray beam):

$$GM(x, y) = \frac{c}{F(x, y)} \quad (1)$$

Where C is an arbitrary normalization constant, $F(x,y)$ is the raw pixel value in a flood projection. For simplicity, detector offset, or dark field, correction is omitted in our equation. Pixel sensitivity differences in a raw CBCT projection, $R(x,y)$ is corrected using,

$$P(x, y) = R(x, y) \times GM(x, y) \quad (2)$$

If an antiscatter grid is placed on the detector, GM method also corrects for pixel value variations due to grid septal shadows. This effect was illustrated using an 1D “scatter-free” projection profile in Fig. 2; a grid septal shadow reduced pixels values from 100 to 50, creating a dip in the uniform signal profile (Fig. 2(a)). A Gain Map generated from a flood projection (Fig. 2(b)) will correct this dip, and uniform signal profile was restored (Fig. 2(c)). In the second example (Fig. 3), a uniform residual scatter is added to the raw projection. It is important to note that a Gain Map is still generated from a “scatter-free” flood projection, since flood projections are acquired without an object in the beam. In this case, correction of the raw signal profile by the Gain Map did not yield a uniform signal profile; corrected pixel values were overcompensated at the septal shadow location. In other words, a grid artifact occurred due to presence of residual scatter in the raw projection and absence of scatter in the flood projection (that was used for Gain Map generation).

2.2 Measurement and correction of residual scatter intensity

Residual scatter leads to an overcompensation, with signal magnitude of d , at pixels in grid's septal shadows after Gain Map correction. In our approach, the magnitude of overcompensation, d , was employed to calculate the residual scatter signal, S , in the image signal. Assuming that scatter is piecewise constant in a small region (e.g. across the area of one grid hole), it is straightforward to show that $S(x,y)$ for a pixel residing in septal shadows is,

$$S_{septa}(x, y) = \frac{d_{septa}(x, y)}{GM_{septa}(x, y) - GM_{hole}(x, y)}, (x, y) \in \text{pixels in septal shadows} \quad (3)$$

Where $GM_{septa}(x,y)$, is the value of gain map in the septal shadow, $GM_{hole}(x,y)$ is the value of gain map in the grid hole. $GM_{septa}(x,y)$ is directly obtained from the Gain Map for a pixel in the septal shadow, whereas $GM_{hole}(x,y)$ is not available at this pixel location. However, $GM_{hole}(x,y)$ for a pixel in a septal shadow can be obtained via interpolation by using the GM values of adjacent pixels residing in grid holes.

This process requires binary labeling of detector pixels to identify whether a pixel is located in the septal shadow or in the grid hole. In our work, the labeling of pixels in grid shadows was achieved by identifying the local minima in flood projections by using a small neighborhood window or kernel.

To calculate $d(x,y)$, raw projections, $R(x,y)$, were first corrected using a Gain Map,

$$P(x, y) = R(x, y) \times GM(x, y) \quad (4)$$

Then, $d(x,y)$ at a grid septal shadow location was calculated using the following,

$$d_{septa}(x, y) = P_{septa}(x, y) - P_{hole}(x, y), \quad (x, y) \in \text{pixels in septal shadows} \quad (5)$$

While $P_{septa}(x,y)$ is simply the pixel value at location (x,y) in the septal shadow, $P_{hole}(x,y)$ was obtained via interpolation value by using the pixel values residing in grid holes surrounding the pixel of interest at (x,y) .

With this approach, $S_{septa}(x,y)$ is calculated for each pixel in septal shadows. Due to smoothly varying nature of scatter, scatter signal in the remaining pixels was calculated via interpolation. After calculating scatter signal in every detector pixel, scatter and Gain Map corrected projection was calculated,

$$P_{cor}(x, y) = [R(x, y) - S(x, y)] \times GM(x, y) \quad (6)$$

CBCT images were reconstructed from $P_{cor}(x,y)$ by using filtered backprojection [7].

2.3 Validation of GSS method in CBCT experiments

CBCT experiments were performed with a Varian TrueBeam CBCT in offset detector geometry (i.e. half fan geometry). A focused, tungsten 2D antiscatter grid prototype with a grid ratio of 12, grid pitch of 2 mm, and septal thickness of 0.1 mm was installed on the flat panel detector. For each CBCT acquisition, 900 projections were acquired at 38 mA and 13 mSec per projection at 125 kVp. Bowtie filter was not used, and 0.9 mm titanium beam filter was in place.

To assess the effect of GSS method on image quality, a Gammex Electron Density Phantom was employed in “small” (20 cm diameter cylinder) and “large” (30 cm by 40 cm ellipse) phantom configurations. CBCT images were reconstructed with and without GSS Method.

To evaluate the effect of GSS method on the reduction of ring artifacts, CBCT images were reconstructed at $0.39 \times 0.39 \times 0.39 \text{ mm}^3$ voxel size, and without pixel binning in projections (pixel size: 388 mm^2). The image noise was calculated in multiple regions of interest to quantify the reduction in ring artifacts.

To assess the CT number accuracy, a separate set of images were reconstructed using $0.9 \times 0.9 \times 3 \text{ mm}^3$ voxels. CT number accuracy was calculated by employing HU loss fraction, K_{HU} ,

$$K_{HU} = 100 \times \frac{ROI_HU_{small} - ROI_HU_{large}}{ROI_HU_{small} + 1000} \quad (7)$$

where ROI_HU_{small} and ROI_HU_{large} are the mean HU values in the same region of interest in small and large phantoms. In essence, K_{HU} is the percent variation in attenuation coefficients as a function of phantom size, which is primarily due to change in scatter and beam hardening conditions.

3. RESULTS AND DISCUSSION

The effect of GSS method was demonstrated in a projection of a Catphan spatial resolution module (Fig. 4). Without correction of residual scatter, Gain Map correction overcompensated the pixel values in septal shadows, which appear as bright grid lines. After correction of residual scatter with the GSS method, line artifacts were suppressed.

The reduction of artifacts in projections translated into reduced ring artifacts in CBCT images. In Fig. 5, high-resolution images of the small Electron Density phantom is shown, where ring artifacts are abundant without GSS method. After application of the GSS method, ring artifacts were suppressed largely. The reduction of ring artifacts was quantified by measuring noise in eight objects in the periphery, and in the central insert. The average image noise was reduced from 78 ± 27 HU to 61 ± 12 HU. There are residual ring artifacts visible in the periphery of the phantom (indicated by blue arrows). These ring artifacts were caused by a problem in the detector readout, i.e. not by residual scatter in projections. Therefore, they remain in images after the application of GSS method.

To calculate the effect of GSS method on CT numbers, both small and large phantom images were reconstructed in low resolution setting (voxel size: $0.9 \times 0.9 \times 3$ mm³). After application of the GSS method, CT numbers increased over all regions of both small and large phantoms and nonuniformity in HU values in uniform density regions was reduced. This effect was more visible in large phantom configuration (Fig. 6). A vertical HU profile across the large phantom is displayed in Fig. 7, indicating the increase in HU values with GSS method. GSS reduced the streak artifacts between high-density objects, which were partially caused by residual scatter (indicated by the blue arrow in Fig. 6). After correction of residual scatter with GSS, high frequency streak artifacts emanating from bone-equivalent objects became more prevalent (such as the cortical bone-equivalent object at 5 o'clock position). This was due to the very low counts in detector pixels at the projected locations of bone-equivalent objects. Scatter correction reduced the counts further in these pixels, and emphasized the effects of stochastic noise.

An important aspect of HU accuracy is the consistency of HU for any given region of interest (ROI) in different phantom sizes. To quantify the HU consistency, HU loss fraction, K_{HU} , was calculated for nine objects in CBCT images of small and large phantoms (Fig. 8). Without GSS, K_{HU} was $9 \pm 5\%$ for all objects analyzed (Table 1), indicating that HU values varied by 9%, when the phantom size was increased from a 20 cm cylinder to 30 cm x 40 cm ellipse. For bone-equivalent objects, the HU loss was higher; for example, K_{HU} exceeded 16% for the cortical bone-equivalent insert (object #4). When GSS method was used, K_{HU} reduced down to $5 \pm 2\%$ for all objects, implying that HU values varied less as a function of phantom size. While one would expect K_{HU} to be zero ideally, other factors, such as beam

hardening, degrade the consistency of HU. In this study, we did not employ beam hardening corrections, which contributed to the increase in K_{HU} values.

The nonuniformity of HU values was measured in water-equivalent sections of small and large phantoms. 9 ROIs were selected around the contrast objects indicated in Fig. 8. Mean HU was calculated in each ROI, and the standard deviation of HUs among 9 ROIs was used as HU nonuniformity metric. Without GSS, HU nonuniformity was 12.7 and 20 HU in small and large phantoms respectively (Table 1). With GSS, HU nonuniformity was 9.7 HU in both small and large phantoms.

4. CONCLUSIONS

We presented a new method, where 2D grid itself is used as a scatter measurement device to measure the scatter transmitted through the 2D grid. The GSS method has two key benefits in regard to 2D grid utilization in flat panel detector based CBCT. First, it provides more accurate CT numbers and reduces shading artifacts due to mitigation of residual scatter transmitted through the 2D grid. Second, GSS method suppresses the ring artifacts caused by 2D grid's septal shadows, since residual scatter is a main culprit behind 2D grid induced artifacts in CBCT.

When compared to previously published measurement-based scatter correction methods, our GSS approach has several advantages: 1) If a 2D grid is utilized in CBCT, it does not require additional hardware to measure scatter, such as beam-stop arrays[8] or fluence modulators[9]. 2) Since 2D grid is placed on the detector, the effect of gantry sag on the septal shadows shapes is minimized, and septal shadow locations are more predictable on the detector plane. Whereas, the beam stop array is placed between the patient and the x-ray source in conventional beam-stop techniques. Beam stop positions, and hence the scatter measurements, are less predictable due to changes in gantry sag characteristics over time. This is a particularly important issue for linac-mounted CBCT systems as reported in the literature[10].

Finally, we believe that, our GSS approach may potentially allow correction of residual scatter at energies higher than the diagnostic energy range. Since GSS method utilizes 20 mm high grid septa as a beam-stop array, primary beam can still be *stopped* at high energies, and scatter intensity can be extracted from pixels located at grid's septal shadows.

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Fig. 1.

(a), Scatter-to-primary ratio (SPR) measured with three different 2D grids and a conventional radiographic grid by using a linac mounted CBCT system. While 2D grid reduces SPR drastically, small amount of residual scatter is transmitted through the 2D grid. Reprinted from ref [2]. (b), Besides reducing CT number accuracy, residual scatter induces ring artifacts in CBCT images due to suboptimal suppression of 2D grid's septal shadows in projections.

Fig. 2. No scatter case:
Grid septal shadow reduces the pixel values from 100 to 50 in a projection. Gain map corrects the shadow perfectly, and uniform signal profile is recovered.

Fig. 3. With residual scatter:
20 units of uniform scatter is added to the projection. Gain Map will overcompensate the septal shadow in this case. Grid shadow appears as a peak in the corrected projection.

Fig. 4.
Projection image of Catphan spatial resolution phantom. Pixel value window: [500 2500]

Fig. 5. High resolution images of the small electron density phantom. Voxel size: $0.39 \times 0.39 \times 0.39$ mm³. Ring artifacts are visible without residual scatter correction. After correction of residual scatter with the GSS method, ring artifacts are suppressed. Center region of the image is displayed in the inset. Ring artifacts in the periphery (some of them are pointed by blue arrows) were caused by an error associated with the detector readout. HU Window: $[-500 \ 500]$.

Without GSS Correction **With GSS Correction** **Fig. 6.**

Large electron density phantom. Voxel size: $0.9 \times 0.9 \times 3 \text{ mm}^3$. HU values are increased, particularly in high density inserts after residual scatter correction with GSS method. Streak artifacts between high density inserts (such as the one pointed by blue arrow) are also reduced after residual scatter correction. HU window: $[-500 \ 500]$. HU profile of the phantoms is shown in Fig. 7.

Fig. 7.
HU profile along the red line in the inset. The change in HU after residual scatter correction with GSS is larger for higher density inserts.

Fig. 8. HU loss fraction, K_{HU} , for different objects in the electron density phantom. (Percent loss in HU values when phantom size is increased from small to large). Ideally, K_{HU} is desired to be close to zero. Object locations are shown in the inset.

Table 1.

HU nonuniformity, HU loss fractions and image noise comparisons.

	Without GSS	With GSS
Water HU nonuniformity (Small Phantom)	12 HU	9.7 HU
Water HU nonuniformity (Large Phantom)	20 HU	9.7 HU
HU loss fraction, KHU	9±5%	5±2%
Image noise (high resolution images)	78±27 HU	61±12 HU