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Region of interest (ROI) computed tomography (CT): Comparison with full field of view (FFOV) and truncated CT for a human head phantom

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Abstract

Cone-beam CT reconstruction can be performed at lower integral dose, by using a non-uniform beam filter between the x-ray source and the patient to obtain good image quality within an ROI with minimal artifacts. To evaluate the method, a human head phantom was placed on a rotary stage. Cone-beam projection images of the phantom were obtained with and without an ROI filter (dose reduction factor ~7). A mapping function was established to equalize the intensity outside the ROI (to compensate for the attenuation by the filter) to the intensity inside by assuming that those features lying both inside and outside very close to the edge of the ROI are the same. Reconstructed images were obtained using equalized projection images for 2 cases: one in which the outside region was smoothed using an averaging filter and the other with no smoothing outside. In addition, a third case was simulated by calculating the average pixel value inside the ROI for each image and assigning this value to all pixels outside the ROI for that image. The images were then back projected using a Feldkamp algorithm. We found that the three cases yield results inside the ROI comparable to those obtained using FFOV projections. In addition, the ROI filter reconstruction with smoothing provides image information outside the ROI comparable to the FFOV reconstruction. CT using an ROI filter provides a means to reconstruct reliable 3D for a volume of interest with greatly reduced integral dose compared to FFOV projections and with minimal artifacts.

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Keywords

Region of interest CT; ROI CT; Volume of interest CT; VOI CT; Area of interest CT; Artifact reduction; Dose reduction; reduced FOV; truncated reconstruction

1. INTRODUCTION

Integral dose can be reduced in Computed Tomography (CT) by blocking the area outside the ROI using an x-ray opaque material like lead. This is designated as truncated CT. Since incomplete data is available outside the ROI, the reconstruction suffers severe artifacts often rendering the image useless. Different approaches have been proposed to reduce these artifacts by estimating or determining data outside the ROI.

The first category of algorithms to overcome ROI artifact estimates the data outside the ROI. Lewitt and Bates² developed an extrapolation technique to determine the truncated data. Ohnesorge et al³, developed an extrapolation procedure which can be incorporated into the convolution step of a filtered back projection. It was observed by Van Gompel et al⁴ that completing the data outside the ROI using a smooth function can improve reconstruction substantially inside the ROI. The second category of algorithms aims at eliminating objects⁴ that corrupt the data inside the ROI in the projection images and removes them to obtain better reconstruction inside the ROI. These estimated or eliminated projections may not model the objects outside the ROI accurately and hence can result in artifacts when used. Moreover they do not provide any information on the reconstructed data outside the ROI.

The third category of algorithm for ROI CT, obtain the data outside the ROI in the projection image. Ruchala et al⁵, used the *a priori* information from treatment planning CT data in improving the limited field of view (LFOV) reconstruction for online CT systems. But the use of this method is limited to the case in which *a priori* information is available. Hooper and Fallone⁶ have proposed a method of combining two or more sets of truncated projection data of an object for a fan beam system by merging their sinograms. But this method is limited to fan beam systems and has not been extended for cone-beam systems. Azevedo et al⁷ proposed a technique of combining projection data acquired using two runs. The ROI is acquired at a high resolution and the outside is acquired at low resolution and the two data sets are then combined to obtain improved reconstruction inside the ROI, assuming no movement has occurred between the two separate acquisitions.

A fourth category of ROI technique called “Local Tomography” was developed by Faridani et al^{8, 9}, which reconstructs using the attenuation measurement along lines very close to the point of interest. But the reconstructed image from local tomography does not represent the map of the attenuation coefficients, but only the edges and boundaries.

In this paper, we propose an ROI CT technique¹⁰ involving an ROI beam filter¹¹ for cone beams, rather than fan beams¹², to obtain a low dose image outside the ROI and high dose image inside the ROI to obtain reduced artifacts in the reconstructed image but at a reduced integral dose. The ROI filtered image is then equalized for the intensity under the ROI filter. The equalized image is then reconstructed to obtain reconstruction comparable to full field

of view not only inside the ROI but also outside. Unlike other methods, no approximations or *a priori* information are required.

2. ROI IMAGE ACQUISITION

The projection images for the study were acquired using a cone-beam system (CBCT) as shown in Figure 1. The system specifications were

1. Infinix C- Arm system from Toshiba Medical Systems Corporation.
2. An Image intensifier based detector with a pixel size of 270 microns and an image size of 1024×1024 .
3. A rotary stage with 0.1 degree precision to acquire images every 2° for a full 360° rotation; thus, 180 projection images were acquired.
4. The Human Head Phantom from The Phantom Laboratory, Salem, NY.
5. An ROI filter 11, 13, 14 is made of a gadolinium oxysulfide Lanex screen of 1.7 millimeter thickness.
6. A reconstructed volume of 2563 voxels with an isotropic voxel size of 700 microns.

As indicated in Figure 1, the x-ray source and detector are stationary, and the object is rotated. The acquired full FOV projection data and other processed projection data are convolved with the Shepp-Logan filter, after which a Feldkamp reconstruction¹⁵ is performed. For obtaining ROI filtered image, the ROI filter is placed between the x-ray source and the patient. The dose reduction due to the ROI filter is approximately a factor of 7.

3. METHOD

3.1 Image equalization – Theory

For images obtained with the ROI filter in the x-ray beam, the pixel value in the image under the ROI filter will have a value smaller than the un-attenuated case as the ROI filter attenuates the beam. Hence, the intensity value in the projection image under the ROI filter has to be equalized prior to back projection.

Beer's law gives the relationship between the intensity of the input x-ray and the intensity after attenuation by the object. It is given by

$$I = I_0 e^{-\sum_i \mu_i x_i}$$

where ' I ' is the intensity after attenuation, ' I_0 ' is the input intensity, ' μ_i ' is the linear attenuation coefficient of the individual features (i) and ' x_i ' is the thickness of these features.

We have not corrected for any variation of scatter across the full FOV; however the scatter intensity should not change significantly across the ROI. If we assume that scatter can be

approximated by a value that is constant, then Beer's law can be modified by adding a constant scatter magnitude (S),

$$I = I_0 e^{-\sum_i \mu_i x_i} + S$$

In the case of ROI filter image, we assume that the scatter magnitude (S) is same for both inside and outside the ROI. The intensity equation for inside ROI will be given by

$$I_{in} = I_0 e^{-\sum_i \mu_i x_i} + S \quad (1)$$

where I_{in} is the intensity of the image inside ROI.

The corresponding equation for outside ROI (i.e., region under the ROI filter) is

$$I_{out} = I_0 e^{-\mu_f x_f} e^{-\sum_i \mu_i x_i} + S \quad (2)$$

where I_{out} is the intensity of the image outside the ROI, μ_f is the linear attenuation coefficient of the ROI filter and x_f is the thickness of the ROI filter.

For the sake of simplicity, let's replace $e^{-\mu_f x_f}$ by the term '1/B', where 'B' is the boost factor ($B > 1$).

Hence, Equation 2 becomes

$$I_{out} = (I_0/B) e^{-\sum_i \mu_i x_i} + S \quad (3)$$

From Equation 1 and 3, we can see that

$$I_{in} = B I_{out} + S(1 - B) \quad (4)$$

which is an equation of a line with slope B and intercept $S(1-B)$. In actual implementation, we obtain the average intensity value along an annular ring of 3-pixel width close to the edge of the ROI both inside (I_{in}) and outside (I_{out}) for different radial positions. By assuming that the intensity very close to the edge of ROI is the same, we can obtain a mapping function between I_{out} (x-axis) and I_{in} (y-axis). This reconstruction will be referred to as **ROI reconstruction**. Since the region outside the ROI received lesser dose than the inside, the outside will be much noisier than the inside as given by the relationship¹⁶,

$$\sigma_r^2 \propto 1/dose \quad (5)$$

where σ_r refers to the relative noise (relative standard deviation) in the image. Two cases were tested for ROI reconstruction. In the first case, the region outside the ROI was not smoothed and the second case, the region outside the ROI and the edge of the ROI was smoothed using a 5×5 averaging filter. The former will be referred to as ***not smoothed ROI reconstruction*** and the latter as ***smoothed ROI reconstruction***.

Images were obtained without the ROI filter in the beam and were used as a standard for comparison. These images will be referred to as ***full FOV reconstruction***.

A third case simulating the case of extrapolating data outside the ROI was also studied. In this case, the regions outside the ROI were given a constant value equal to the average intensity of the region inside the ROI. These images will be referred to as ***Average reconstruction***.

3.2 Image equalization - Implementation

The projection images for the three cases as described in section 3.1 were created for ROI reconstruction. Figure 2 shows examples of the projection images obtained with the ROI filter in the beam. Figure 2a is the ROI filtered projection image before equalization of intensity. Note the difference in the intensity between inside and outside the ROI. Figure 2b is the ROI filtered image after equalization but before smoothing using the average filter. Only the content outside the ROI was equalized and the content inside was not modified. Figure 2c is the ROI filtered image after equalization and after smoothing using the average filter. The smoothing is extended to 3 pixels inside the ROI, to eliminate the edge of the ROI. In all the three cases, the profile at the bottom indicates the intensity along the line in the image. The region under the ROI filter in the projection image will be referred as *Outside ROI* and the other region will be referred as *Inside ROI* and are labeled in Figure 2a.

3.3 Metrics

Qualitative metrics like details visible and artifact reduction in the reconstructed ROI were used to compare the effectiveness of ROI CT. For quantitative comparison, the difference image between the full FOV reconstructions and the smoothed and not smoothed ROI reconstruction and the Average reconstruction were obtained. The Mean square error (MSE) value between the full FOV reconstruction and other three reconstructions was calculated for both inside and outside the ROI. Percentage error (PE) defined as ratio of MSE to the intensity value of the bone in the reconstructed image was also calculated.

4. RESULTS

4.1 Results for central slice (Large ROI)

In Figure 3, we present the results for reconstruction of the central slice. The top row is the reconstructed image (all images in that row have the same window/level) and the bottom row (all images in that row have the same window/level) is the difference image. The full FOV reconstruction (Figure 3a) and smoothed ROI reconstruction (Figure 3b) are similar not only on the inside ROI but also on the outside. The region outside ROI is blurred in Figure 3b due to the average filter used in the projection images during equalization. The not

smoothed ROI reconstruction (Figure 3c) results in a reconstructed image which is close to the full FOV reconstruction inside the ROI but is noisier on the outside, when compared to smoothed ROI reconstruction (Figure 3b). This renders the visualization of features outside the ROI difficult. Average reconstruction (Figure 3d) produces reconstructed image with information only inside the ROI, but it does not provide any information on the outside. It can be seen in Figure 3c, there are two circles corresponding to the edge of the ROI, as the filter was not centered with respect to the image. The region inside the inner most circle will be designated as the inside ROI region for all subsequent metrics. The size of the inner region (Inside ROI) is 18% of the full FOV.

In the difference image (Figure 3e) between full FOV reconstruction and smoothed ROI filter reconstruction, we see that the information inside the ROI is noisy with many of the features located in the original image missing, indicating a good correspondence between full FOV and ROI filter reconstruction. This is also indicated by the low value of MSE of 232.7 (Table 1). For the difference image for not smoothed ROI reconstruction (Figure 3f) and Average reconstruction (Figure 3g), the features both inside and outside are visible, indicating loss of contrast due to not smoothing the projection data outside and also by roughly estimating the projection data outside. This is reflected in the value of MSE and PE for the 2 cases.

4.2 Image of Inside ROI

Figure 4 is the zoomed version of Figure 3. The region zoomed is shown by a solid circle in Figure 3a. Note that the inside ROI looks similar in all cases, albeit with a loss of contrast described earlier. This indicates that even an approximate estimation of the projection data outside the ROI results in a good reconstruction inside the ROI. But by acquiring projection data outside ROI at a lower dose, we can obtain good reconstruction both inside and outside the ROI.

4.3 Results for slice 1 cm from central slice (Small ROI)

Figure 5 lists the results for reconstruction of a slice located 1 cm from central slice. Since the region inside the ROI was circular in the projection image (Figure 2a & Figure 1c), these slices have a *smaller ROI size* when compared to reconstructed image from central slice (Figure 3), which has the maximum ROI size.

The top row is the reconstructed image (all images in that row have the same window/level) and the bottom row (all images in that row have the same window/level) is the difference image. The size of the ROI is 13% of the FFOV. The full FOV reconstruction (Figure 5a) and smoothed ROI reconstruction (Figure 5b) are similar not only on the inside ROI but also on the outside. The region outside ROI is blurred in Figure 5b due to the average filter used in the projection images during equalization. Also the edge of the ROI can be seen in the reconstructed image. Since anatomical features do not have a regular shapes like circles, it will be unlikely that the edge of the ROI to be confused with anatomical features. The not smoothed ROI reconstruction (Figure 5c) results in a reconstructed image which is close to the full FOV reconstruction inside the ROI but is noisier on the outside, when compared to

smoothed ROI reconstruction (Figure 5b). Average reconstruction (Figure 5d) produces reconstructed image with information only inside the ROI.

In the difference image (Figure 5e) between full FOV reconstruction and smoothed ROI filter reconstruction, we see that the information inside the ROI is noisy with many of the features located in the original image missing, indicating a good correspondence between full FOV and smoothed ROI filter reconstruction. This is also indicated by the low value of MSE of 210.1 (Table 1). For the difference image for not smoothed ROI reconstruction (Figure 5f) and Average reconstruction (Figure 5g), the features both inside and outside are visible, indicating loss of contrast due to not smoothing the projection data outside and also by roughly estimating the projection data outside. This is reflected in the value of MSE and PE for the 2 cases.

5. CONCLUSION

ROI CT can provide an image quality comparable to that obtained with full FOV acquisitions even with a very low integral dose (the dose reduction factor was ~ 7 in this experiment). The quality of reconstruction both inside and outside the ROI is independent of ROI size as demonstrated in Figure 3 and 5. This provides a promising means for reducing the dose to the patient during image acquisition. While the quality of the reconstructions will be affected by the information content outside the ROI, e.g., uniform versus highly varying and/or high contrast, we believe that ROI-CT can provide high quality reconstructions with reduced dose outside the ROI primarily because in ROI-CT, data is actually acquired outside the ROI as opposed to extrapolation or elimination of data inside the ROI. Note also that no *a priori* information is required for this technique.

ROI-CT could also be performed using two scans and/or detectors, e.g., one scan could be obtained at low dose and with a low resolution full FOV detector and a second scan at a higher dose and using a high resolution ROI detector. The two sets of projection data would then be combined appropriately before reconstruction. An alternate approach would be to use a hybrid detector that combines high resolution in the ROI and low resolution outside the ROI in combination with an ROI x-ray filter to reduce the dose outside the ROI. The smoothed ROI reconstruction simulates the low resolution detector on the outside by using an averaging filter.

Thus, we believe that ROI-CT could be used to:

1. Substantially reduce artifacts in reconstructed data both inside and outside the ROI by acquiring the information in the peripheral areas of the projection image,
2. Improve the spatial resolution within the reconstructed ROI when a high resolution detector is used in the ROI,
3. Reduce the integral dose to the patient but still obtain comparable reconstruction with full FOV acquisition and
4. Reduce scattered radiation in cone-beam imaging.

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Figure 1.

a) Schematic of the setup for filtered image acquisition b) Top view of the setup c) Photograph of the setup

Figure 2.

Actual and equalized projection images. The top row is the projection image and the bottom row is the profile across the line shown in the corresponding image. a) The full FOV projection image before equalization. b) The projection image after equalization but before smoothing outside the ROI. Note that the profile has spikes corresponding to the edge of the ROI and also in the region outside the ROI. c) The projection image after equalization and smoothing outside the ROI. The spikes corresponding to the edge of the ROI and the region outside the ROI are reduced.

Figure 3.

Reconstructed results for central slice a) The full FOV reconstruction image b) The smoothed ROI reconstruction c) The not smoothed ROI reconstruction d) Average reconstruction e) Difference image between full FOV reconstruction and smoothed ROI reconstruction f) Difference image between full FOV reconstruction and not smoothed ROI reconstruction g) Difference image between full FOV reconstruction and Average reconstruction

Figure 4.

The region inside the ROI for slices from Figure 3 (shown by the solid circle in Figure 3a) a) The full FOV reconstruction image b) The smoothed ROI reconstruction c) The not smoothed ROI reconstruction d) Average reconstruction

Figure 5.

Reconstructed results for slice 1 cm from central slice a) The full FOV reconstruction image b) The smoothed ROI reconstruction c) The not smoothed ROI reconstruction d) Average reconstruction e) Difference image between full FOV reconstruction and smoothed ROI reconstruction f) Difference image between full FOV reconstruction and not smoothed ROI reconstruction g) Difference image between full FOV reconstruction and Average reconstruction

Table 1

MSE and PE for slices corresponding to the slices in Figure 3 and 5

Slice detail	Parameter	Smoothed ROI Reconstruction		not smoothed ROI Reconstruction		Average Reconstruction	
		Inside	Outside	Inside	Outside	Inside	Outside
Central slice	MSE	232.7	206.9	257.7	562.6	253.1	-
	PE (%)	1.09	0.97	1.21	2.63	1.18	-
Slice 1 cm away from central slice	MSE	210.1	185.0	255.2	468.1	225.8	-
	PE (%)	0.99	0.87	1.19	2.03	1.05	-