Post Scan Correction of Step, Linear and Spiral Motion Effects in CT Scans

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ABSTRACT
X-ray CT scanners provide images of transverse cross sections of the human body from a large number of projections. During the acquisition of image data, the motion of patient produce effects that appear as blurring, doubling, and distortion in the reconstructed images. This degrades the image quality and can lead to wrong diagnosis. In this work a technique has been developed and tested that removes these effects in brain CT scanning for step, linear and rotational motions of head during CT scanning process. The motion of head is modeled as rigid body motion. The three-dimensional motion information is used to correct the CT data before reconstructing the image from it. The images are found to be free of motion effects. The results demonstrate the validity of this approach for above stated types of head motion of patients during CT data acquisition process.

General Terms
Medical Imaging, Tomography, Motion Objects, Mechanism.

Keywords
Computed Tomography, Scans, Phantom, Objects.

1. INTRODUCTION
X-ray CT scanners provide images of transverse cross sections of the human body from a large number of projections. It is assumed in the mathematical reconstruction mechanisms that are used in CT imaging that the object remains stationary during the acquisition of all projections. If the object moves during the data acquisition process then the CT images formed by the reconstruction mechanisms show motion effects. In clinical CT imaging patients move during data acquisition, as a result of this movement different projections yield conflicting information about the internal structure of the patient. The effects in CT images are the direct result of the reconstruction mechanism's attempt to reconcile conflicting data. These motion effects are one of the major causes of the degradation of image quality for CT images. Motion effects are frequent in scans of unconscious or paediatric patients; however, they occur even in scans of conscious adult patients.

During the data acquisition process, motion in the patient's body like blood flow, head motion, and patient mobility creates effects that appear as blurring, replication, and twist in the reconstructed image and can cause wrong judgment. These effects can range from slight motion blurring to major stripes across the complete image. Some methods used for motion compensation in CT imaging are (1) fast-imaging techniques with breath-holding — an ultra-fast scanning time (such as less than 100 ms in CT) can remove motion effects (Ritchie1994); (2) multi-acquisition or overlapping half-scans (Parker1981), then choosing the images with the fewest motion effects or averaging to haze out stirring bodies; (3) gating to one or both of the cardiac and respiratory cycles, such as by centering data acquisition on the midpoints of the quiescent period of respiration, and (4) correction of data using different post-processing techniques, either in projection space or in image space. These methods are useful in some applications. But they have problems as well. The fast-imaging techniques result in low signal-to-noise ratios (SNR). Averaging methods can improve SNR, but objects with fine detail that experience continual motion during scanning can haze out. Multi-scanning exposes the patient to unnecessary radiation which can be harmful for health. Gating requires advance information about the cardiac or respiratory cycle. The best approaches are the post-processing techniques to correct corrupted data before image is reconstructed. We proposed a simple algorithm in this regard in our earlier work that dealt with two-dimensional motion correction [1] and performed some preliminary tests that showed promising results. In this work, we have developed the complete methodology based on this approach for correcting head motion in three dimensions and have conducted detailed simulations which show the effectiveness of our technique for all types of head motion during CT scan.

The proposed method is a technique to remove the motion effects of head motion during brain imaging by tracking the head motion. In this method the head motion is modeled as the motion of a rigid body. During the process of CT scan, motion of head is precisely recorded using a tracking system, which consists of infrared cameras attached to a computer. The information collected by the motion tracking system is used to correct the data collected by the CT scanner. This corrected data is later used to reconstruct the final image. This method requires an accurate tracking scheme for each type of potential motion. Tomographic projection data (sinogram) encode the subject's anatomy information, while its motion information during the data acquisition is collected by the motion tracking system. The projection data are then adjusted and interpolated to compensate for the motion effects and a motion-corrected image is reconstructed by the conventional filtered back-projection (FBP) method (Herman 1980).

In order to demonstrate the validity of this proposed method, we use CT projection data which is simulated for a moving phantom. It was assumed that the precise information about the motion of the phantom is also available. This motion information is used to modify the sinogram data which is later used to reconstruct the final image. As expected, the final image is free of the motion effects. In this work, we assumed very simple kind of motions for the phantom. These motions are too simple to be realistic but are sufficient to establish the validity of the proposed method. In section 2 we discuss the related work, section 3 discusses some methods to deal with motion effects in CT scans. Section 4 presents the details of the mechanism, section 5 illustrates different types of motions during scans and section 6 presents the simulated results. Finally section 7 concludes the paper.

2. RELATED WORK

Computed Tomography is an important medical imaging technique which is basically x-ray scanning of different parts of human body. Patients are directed to stay fixed at one position so that motion objects do not appear in scans. This is not possible in case of small children and elderly patients. Even in normal adults motion objects can be seen in CT scans. There are different methods to deal with this problem and most important are the post scan mathematical techniques to remove or minimize motion effects. Some of these techniques are given are [1]-[11]. Different mathematical techniques that have been developed are suitable for different types of CT scans for example some techniques are specially developed for head scans [1]-[7], some are developed for respiratory scans [9]-[10] and some are developed for dental scan [11]. The basic principle in head CT scans is construction of skull called phantom through filtered back-projection of CT data. Some earlier work done in this regard also uses infrared motion tracking system in order to collect motion data synchronized with CT data. Using this motion data it is possible to correct motion objects before image is reconstructed. Christian D. et al have done similar work in this regard but the focus of their work is magnetic resonance imaging. Dhanantwari A. et al [5] have done work in CT scans where they use a spatial overlap correlator scheme to accurately track organ motion in computed tomography imaging systems. They apply adaptive interference cancellation (AIC) methods which treat the output of the spatial overlap correlator as noise interference at the input of the AIC process. The downside of this approach is hardware modifications. In an earlier work [1] we proposed a simple algorithm based on motion tracking system data and we tested it for simple head motions. This work has been enhanced and improved in this paper and we have tested its efficacy for complex head motions as well.

In [9] we are told that the respiratory motion during collection of computed tomography (CT) projections generates structured effects and a loss of resolution that can render the scans unusable. Suspending respiration is even difficult then keeping other parts of body still. The authors present an algorithm that is used to minimize motion effects in CT scans caused by respiration. The basic idea is that the object cross section goes through time-varying enlargement and dislocation along two axes. Based on this model a filtered back-projection algorithm is proposed for parallel projections. The result is used to construct a reconstruction algorithm for fan-beam projections. The algorithms are validated through computer simulations and scans on a commercial CT scanner. The authors suggest that this method can also be used in single photon emission computed tomography (SPECT), positron emission tomography (PET), and magnetic resonance imaging (MRI). In [10] Lewis et al. propose an algorithm capable of minimizing respiratory motion blurring effects in cone-beam computed tomography (CBCT) lung tumor images based on the motion of the tumor during the CBCT scan. The tumor motion path and probability density function (PDF) are reconstructed from the acquired CBCT projection images using an earlier algorithm proposed by them. They assume that the effects of motion blurring can be represented by convolution of the static lung (or tumor) anatomy with the motion PDF, and define a cost function. They perform de-convolution through iterative minimization of this cost function. In [11] Naranjo et al. state that the presence of metallic objects in human jaws, such as amalgam or gold fillings results in effects in CT scans like streaking and beam hardening which makes the reconstruction process difficult. They have developed a new method that executes a morphological filtering in the polar domain resulting in images less affected by effects without causing smoothing of the anatomic structures. The basic algorithm for CT image construction can be understood through [12]-[14].

3. MOTION EFFECTS IN CT AND THEIR COMPENSATION

The problem of organ motion effects in x-ray computed tomography (CT) systems became an important issue when x-ray CT scanners became common for imaging human body. There are two approaches to deal with the problem of organ motion effects. These approaches can be classified as Preventative methods and Corrective methods.

In preventive methods the main idea is to regulate the scanning process to produce a data set with minimized motion effects compared to a standard x-ray CT scan. Some of the techniques in preventive methods are breath holding i.e. telling the object to remain still, but this method fails in case of children and unconscious patients and also fails as a result of blood flow, cardiac motion, etc. Scanner-organ motion synchronization is by finding the angle at which to start scanning process. But this angle adjustment is very critical and requires assessment of the motion cycle, the Electrocardiogram (ECG) in the case of cardiac motion, prior to scanning the object, and to assess when the heart will be at rest and activate the scanner based on this calculation. Another method is scan time reduction which helps in reduction of cardiac motion effects, but the improvement is not marked. Over-scanning is also used by taking multiple scans and then averaging them to get final scan. But this method exposes patients to undesirable radiation which is harmful. Also correction is not very marked. Gating is another method which is considerably good and effective. This is based on the concept that most motions are repetitive and have regular patterns. In this method projection is acquired at a specific position in motion cycle. The scanner is stopped after some projections and restarted when that position is reached again. The drawback in this method is long scan time.

In corrective methods scan data is corrected before image is reconstructed. One of the approaches are the filtering approaches in which spectral properties of motion effects are determined and then filtering is applied to remove them. It can distort the final image. Another technique is to model motion and then apply corrective algorithms. But these methods assume motion patterns and if that is incorrectly predicted then it can give poor results. This method is also used in magnetic resonance imaging. Another method is the back-projection method but it needs a lot of physical effort to precisely depict the motion of each pixel and is impractical for real-time CT scans.

4. MECHANISM

4.1 Tracking System

A motion tracking system is used to report location of object throughout the process of CT scan. This tracking system has to be time-synchronized with scanner. The shift and rotation of the object during the acquisition of each projection in respect to the first acquired projection is measured by means of infrared tracker. Motion tracking system to be used for our proposed algorithm has to report head motion in three dimensions. The CT data is shifted and rotated back in accordance to these measured parameters. The time needed to acquire a single projection is much shorter than the time needed between acquiring subsequent projections. Hence, motions of the head during the acquisition of a single projection are negligible and the effects of motion are visible between subsequent projections. The simulated motion tracking data has been used for motion correction in this project. The simulated data provides the motion of head phantom in x-y plane. This data is used to correct the projections in the projections matrix. Image data is the matrix of projections and is obtained from the CT system as CT data for the object. Motion data is the movement of object in x and y directions and the angle of motion reported by the motion tracking system at every instant during data acquisition. In this mechanism object is head phantom which is created using phantom function in MATLAB. CT data is generated by calculating projections of head phantom from 0 to 180 degrees. This is accomplished by using "radon" function in MATLAB. It can also be accomplished by taking line integrals without using radon function. Motion data is simulated data reporting x- , y- and z- direction movement of object and the angle of movement with x-axis.

4.2 Mathematical method

A mechanism is developed which takes the Image data (matrix of projections) and motion data and shifts Image data based on the information from motion data. Due to head motion, the 'location' of projections within the sinogram matrix change. As shown in Figure 1, this amount of relocation of data is governed by

$$d = r * \sin(theta_i) * \sin(phi)$$

where $r = \sqrt{x^2(t_i) + y^2(t_i) + z^2(t_i)}$ and $theta = a - b$

theta = angle between direction of motion x-rays

a = angle of projection and

b = angle between direction of motion and x-axis

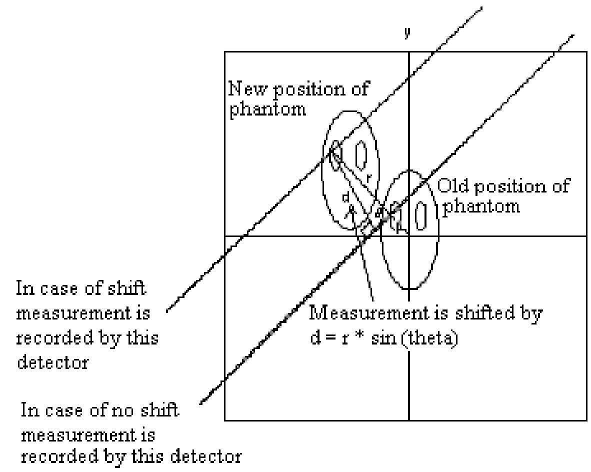


Figure 1: Measurement is shifted by d = r * sin θ

The algorithm calculates the shift in the detector measurements due to object motion and fixes the shift. The Image formed from this corrected data is free from motion effects. The algorithm is developed for translational step, linear and rotational motion of head.

Algorithm

1. Projection data for 0 to 180 degree rotation of scanner is collected
2. Rotation of scanner angle = angle that x-rays form with x-axis
3. Synchronized motion tracking system report object position and tilt angle of object
4. At time t_i, object moved to position $\left(x(t_i), y(t_i), z(t_i)\right)$
5. Shift in object is calculated as $d = \sqrt{x^2(t_i) + y^2(t_i) + z^2(t_i)}\,\sin\phi(t_i) * \sin(phi)$ where $$\phi(t_i) = \tan^{-1}\left(\tfrac{y(t_i)}{x(t_i)}\right) - \alpha(t_i) and phi = \cos^{-1}\left(\frac{z}{d}\right)$$
6. Shift subtracted from data at all instants
7. Filtered back-projection algorithm applied to construct corrected image

5. TYPES OF MOTIONS

The proposed method is applicable for three types of motions these are step motions, linear motions and rotational or spiral motions. This method records head motion in three dimensions which is realistic and corrects it. We illustrate these shifts in this section.

5.1 Illustration of Horizontal Shifts

Figure 2 and Figure 3 show a shift of 0.1 in a horizontal direction. Detector measurement is shifted by 0.1 for θ = 0 and 180 degrees and is shifted by 0 for θ = 90 degree. Here it can be seen that for 0 or 180 degree position of scanner the angle between direction of motion and x-rays is 90 degree, in this case the measurement is shifted by 0.1*sin 90 = 0.1.

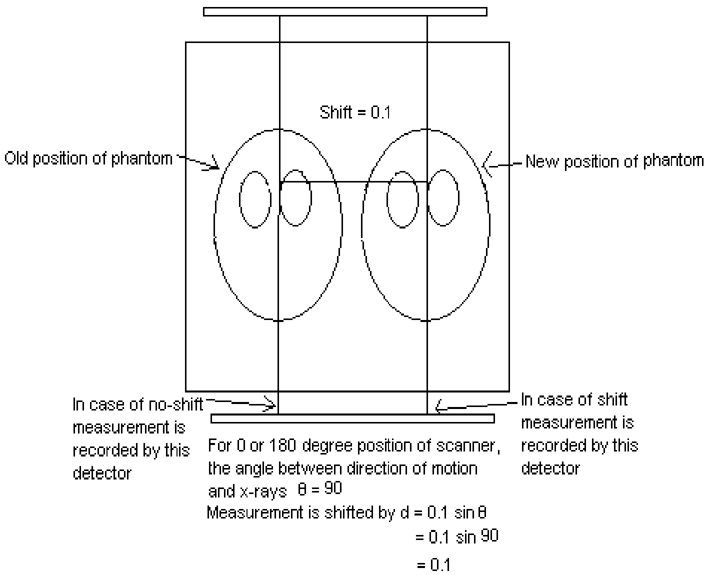


Figure 2: Illustration of 90 degree angle horizontal shift

Similarly for 90 degree position of scanner the angle between direction of motion and x-rays is 0 degree and it results in measurement data shifted by 0.1*sin 0 which is equal to 0. Thus there is no problem in collected data and image reconstructed from this data is free of motion effects.

5.2 Illustration of Vertical Shifts

Figure 4 and 5 show a shift of 0.1 in a vertical direction. Detector measurement is shifted by 0 for θ = 0 and 180 degrees and is shifted by 0.1 for θ = 90 degree. In the first case, for 0 or 180 degree position of scanner when there is vertical motion of object, the angle between the direction of motion and x-rays is 0 degree which results in 0.1*sin 0 which is equal to 0 hence no adjustment of data and the reconstructed image is correct even if there was vertical movement.

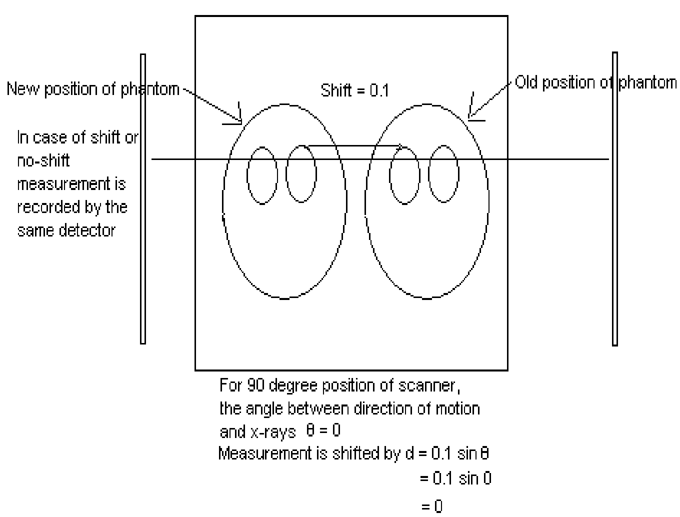


Figure 3: Illustration of 0 degree angle horizontal shift

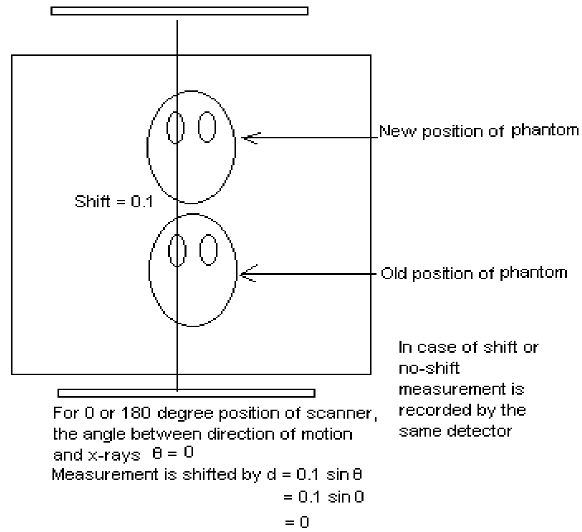


Figure 4: Illustration of 0 degree angle in vertical shift

Similarly when there is vertical shift in object but the angle between the direction of motion and x-rays is 90 degree, in this case the measurement gets shifted by 0.1*sin 90 which results in 0.1 and thus this data is corrected by algorithm prior to reconstruction and the resulting image is free from motion effects.

6. SIMULATION RESULTS

In this section we show results obtained by simulations in Matlab. We simulated translational step motions in horizontal and vertical directions and tested the algorithm. We then simulated linear continuous motion of object and then we simulated relatively complex but real motion that is rotational. Rotational or spiral motion of head is the most realistic because in reality, only translational motion is very rare. The results show drastic improvement in reconstructed images when our method is used.

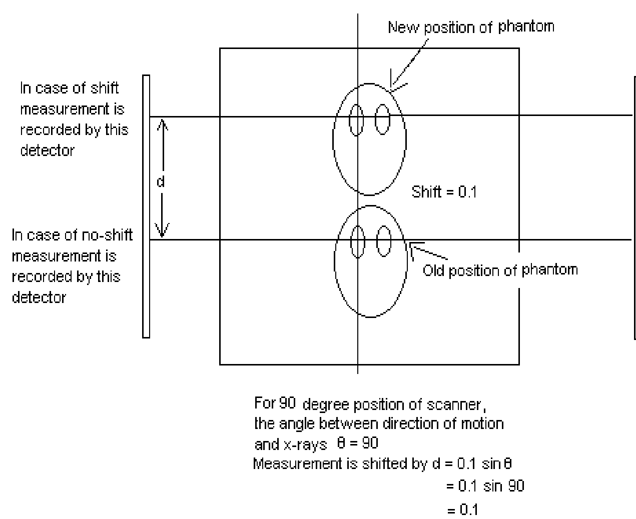


Figure 5: Illustration of 90 degree angle in vertical shift

6.1 Translational Step Motion

The step movement of head in an arbitrary direction and the image distorted due to these motion effects and the corrected images are shown in Figure 6 and 7. Figures also shows the corrupted and corrected sinograms from which images have been reconstructed. It is assumed that during data acquisition for CT scan the head was at position 1 for half the time and moved to position 2 for remaining half time.

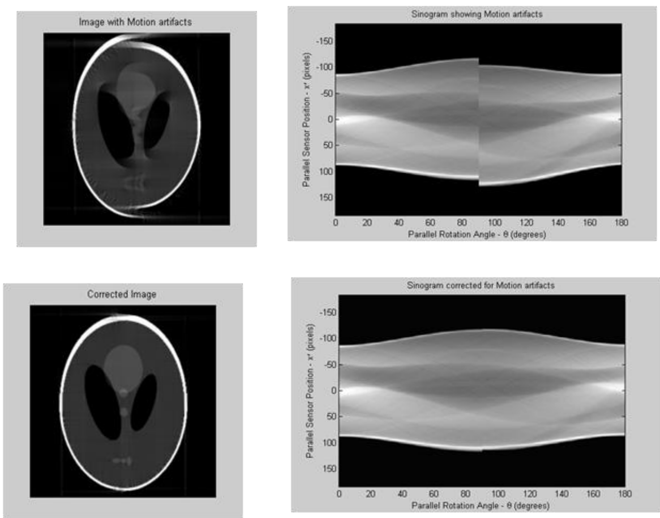


Figure 6: (a) The Image showing motion effects due to shift in a step and the sinogram from which this image is reconstructed (b) The corrected image and the sinogram of image that is free from the motion effects

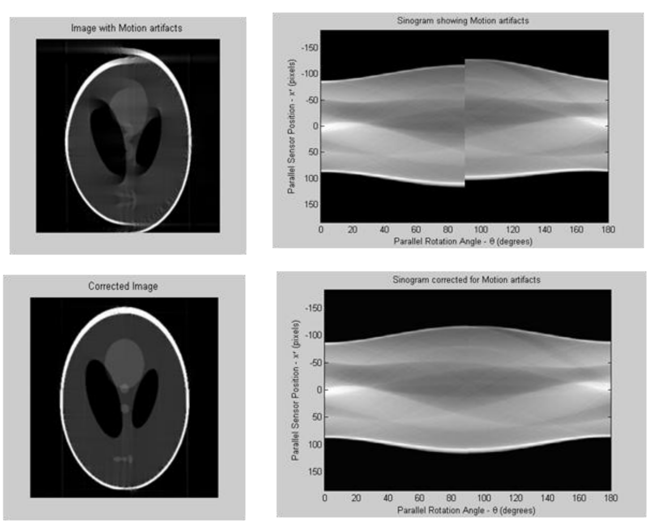


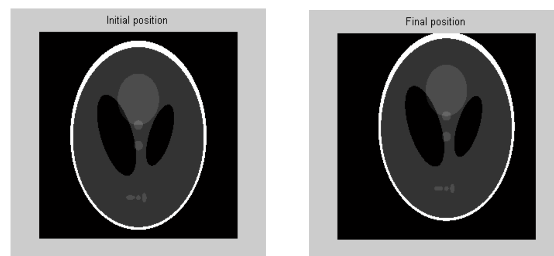
Figure 7: (a) The Image showing motion effects due to shift in a step motion and the sinogram from which this image is reconstructed (b) The corrected image and the sinogram for image that is free from the motion effects

6.2 Translational Linear Motion

The translational step motion is a shift or a sudden jump of the object (head phantom). In real practice we encounter a smooth linear motion in an arbitrary direction. In other words, while scanning takes place from 0 to 180 degrees, the object moves (with a constant speed) from position 1 (x_1,y_1,z_1) to position 2 (x_2,y_2,z_2). This means we get an incremental new position of head for every angle in CT scan. This type of head motion and its correction is shown in this section. The sinogram is shifted continuously from angle 0 to 180 degree measurements until the head is placed in its new position. The smooth linear motion of head in an arbitrary direction and the images and sinograms for corrupted and corrected image are shown in Figure 8.

6.3 Rotational and Spiral Motion

The most realistic motion is rotational or spiral motion which is expected in more than 90% of CT scans. This motion is simulated and corrected as shown in Figure 9 and 10.



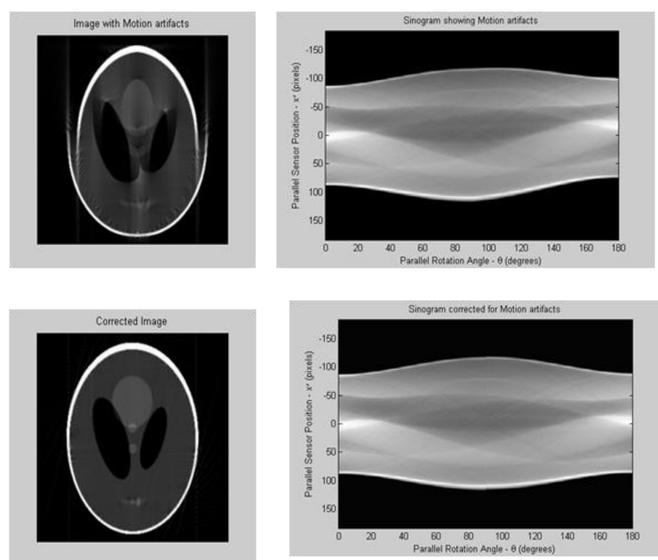


Figure 8: (a) The Image showing motion effects due to translational smooth linear motion of head and the sinogram from which this image is reconstructed (b) The corrected image and the sinogram of image which is free from the motion effects

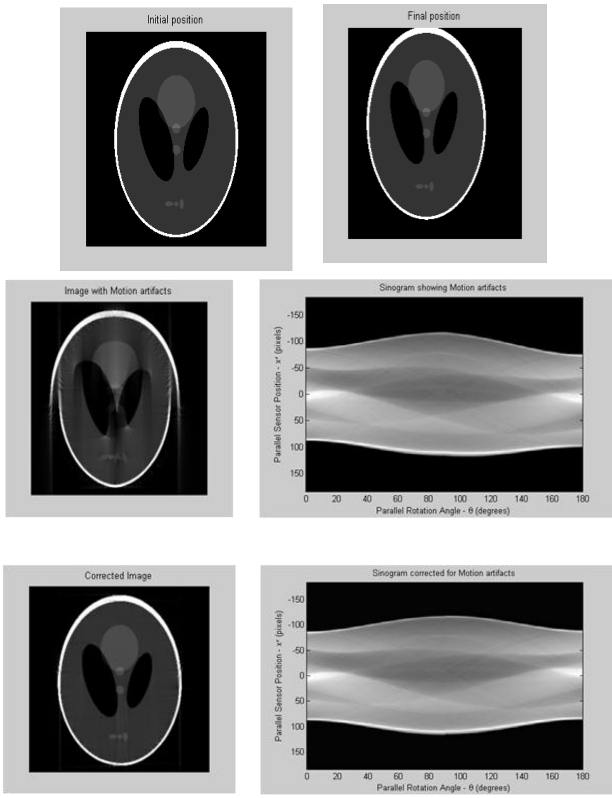


Figure 9: (a) The Image showing motion effects due to spiral or rotational shift and the sonogram. (b) The corrected image.

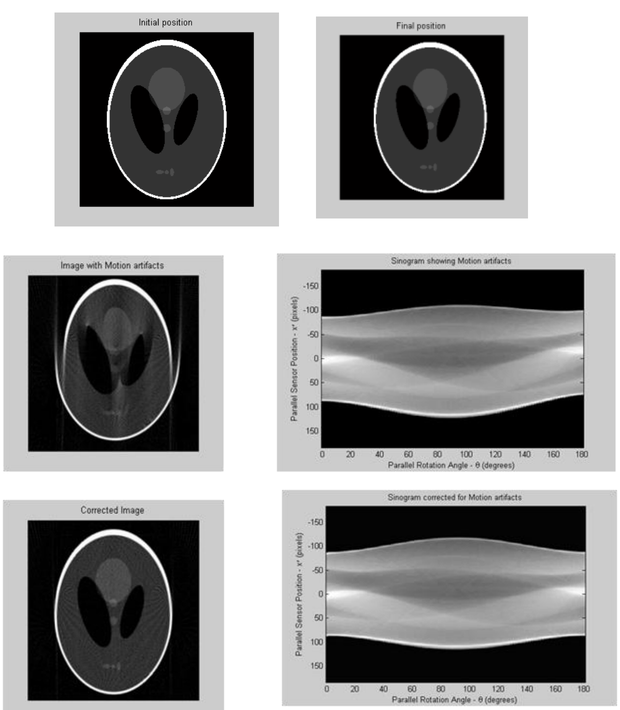


Figure 10: (a) The Image showing motion effects due to spiral of rotational motion in another direction and sinogram from which this image is reconstructed (b) The corrected image

7. CONCLUSION

The problem of motion effects is common in x-ray CT systems. There are some types of motion that may seem controllable, such as respiratory motion and patient movement. There are other types of motion that are difficult to manage, such as breathing and cardiac motion. These motion effects cause distortion in the reconstructed x-ray CT image. This is due to the fact that reconstruction mechanisms assume no motion effects in the raw x-ray CT data sets, as if it was a single instance data. But actually the data is not acquired instantaneously, but over a period of time during which patient moves. The problems in reconstructed image are in the form of motion effects that look like stripes, lines and fading. This can be lead to wrong medical diagnosis. There are many methods for solution to this problem. Some are simple while some are complex. This work is an extension of an earlier work in this direction and presents the technique of compensating head motion effects in three dimensions by adjusting the projections based on three-dimensional motion information from the simulated motion data. This technique is useful in compensating head motion effects since other type of organ motion effects may require more suitable techniques. The technique has been tested for simple and complex motion of head during data acquisition and shows promising results.

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