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Evaluation of Digital Linear Tomosynthesis Imaging of Total Joint Arthroplasty Using an Amorphous Selenium Flat-panel Detector

Tsutomu Gomi

Department of Radiology, Shinshu University Hospital

Introduction

Total joint arthroplasty has become one of the most frequent and successful surgical procedures. Although the quality of life for these patients is dramatically improved, the success of this procedure has led to an expansion of its potential recipients to younger, more active populations. In addition, these replacements in many cases are lasting longer than was initially expected, and the bone physiology of the recipient may have changed from the time of the procedure simply as a result of aging. Radiographic evaluation of these replacements, both in the initial fixation period and as the device ages, is essential to address any failure that may arise. For example, imaging during the initial fixation state can be used to evaluate the extent of bony ingrowth associated with a non-cemented device, helping to distinguish it from fibrous ingrowth. Radiography also can be used to evaluate the amount of wear of particular components of the re-

placement that may eventually lead to its loosening. The knowledge obtained from radiographic imaging may also prove invaluable in the design of future successful devices.^{1,2)}

There are, however, practical limitations of the successful application of radiography to this evaluation. The metallic components of these devices are essentially radiopaque, which make obtaining radiographic information about them exceedingly difficult. For example, it is practically impossible to view the femoral head section within the acetabular component of a total hip replacement (THR). On the other hand, the polyethylene component is radiolucent, and the evaluation of any wear needs to be inferred from the spatial relationship of the two metallic components on either side of it. If one does not obtain the proper two-dimensional (2D) projection through the hip joint, this estimate is fraught with error. In addition, to compare such evaluations of wear over

Summary

The purpose of this study was to evaluate the clinical potential application of digital linear tomosynthesis in the imaging of hip prostheses. Volumetric x-ray digital linear tomosynthesis was used to image hip prostheses. The device used for an object of comparison assumed x-ray radiograph and computer tomography (CT) imaging. The results showed that the visualization of hip prostheses is improved by the ability to produce sectional images that blur overlying structures and yield three-dimensional (3D) information of the hip joint. The streak artifacts from the metallic components of CT devices limit the usefulness of CT in this application. The flexibility of digital linear tomosynthesis, as well as the fact that through an appropriate choice of modified filtered backprojection (FBP) algorithms it can suppress streak artifacts, potentially makes it an appropriate approach for evaluating hip prostheses. The potential of digital linear tomosynthesis in the evaluation of hip prostheses was demonstrated. Future investigations will study the ability of digital linear tomosynthesis to quantify the spatial relationships between the metallic components of these devices as well as the ability of digital linear tomosynthesis to identify bony changes of diagnostic consequence.

Key words: digital tomosynthesis, total joint arthroplasty, artifacts

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信州大学医学部附属病院 放射線部 五味 勉 宛

time would require obtaining essentially the same exact projection at each instance. Achieving the exact alignment required for comparable evaluation is particularly challenging because these determinations typically will extend over a number of years.

For these reasons, a three-dimensional (3D) rather than a 2D approach should substantially enhance the radiographic evaluation of total joint arthroplasty. If one could view these data as either a series of tomographic slices or as a 3D-rendered image, then one potentially could use a projection from the optimal viewing angle to evaluate the device. Sequential 3D images could be similarly oriented or even coregistered to each other in order to quantitatively evaluate changes in the status of the device. Objective quantification of the orientation or the spatial relationship between the components of a total joint replacement is also more feasible with a 3D representation of the joint.

Interest in tomosynthesis and its clinical applications has been revived with recent advances in digital x-ray detector technology. Conventional tomography technology provided planar information of an object from its projection images. In tomography, an x-ray tube and an x-ray film receptor were continuously moved in opposite directions on opposite side of the object. The relative motion of the tube and the film was predetermined based on the location of the in-focus plane.³⁾ Only one image plane was generated by a scan, and multiple scans were needed to provide a sufficient number of planes that would cover the selected structure in the object. Tomosynthesis acquired only one set of discrete x-ray projections, which could be used to reconstruct any plane of the object retrospectively.⁴⁾ Tomosynthesis has been investigated in applications such as angiography, chest imaging, hand joint imaging, pulmonary imaging, dental imaging, and breast imaging.⁵⁻¹⁰⁾ A review of tomosynthesis techniques was given by Dobbins et al.¹¹⁾ Various methods of tomosynthesis reconstruction have been explored. Tomosynthesis was shown to statistically significantly outperform planar imaging.

In this report, we focus on the potential application of linear motion digital linear tomosynthesis using an amorphous selenium flat-panel detector in which a modified filtered backprojection (FBP) reconstruction algorithm for enhanced performance is used for the imaging of hip prostheses cases.

1. Materials and Methods

1-1 Modified FBP algorithm¹²⁾

Basic shift-and-add tomosynthesis is equivalent to simple unfiltered backprojection. However, tomosynthesis acquires data over a 3D volume rather than a 2D area (i.e., slice) as with regular CT, and thus one must address 3D Fourier space when considering backprojection with tomosynthesis. The 3D version of the Fourier slice theorem states that when a 2D image of an object is acquired at some particular orientation to that object, the 2D Fourier transform of that projection image yields a plane through the 3D Fourier space of the object. [Again, the assumption is made that pixels are logarithmically processed so that they are proportional to the line integral of attenuation coefficients along respective rays through the object (Fig. 1)] As the angle of orientation of the 2D detector is moved with respect to the object, a volume of data is swept out in 3D Fourier space. Because only a limited angle is swept out during tomosynthesis acquisition (tomosynthesis being a form of limited-angle tomography), not all of the volume of 3D Fourier space is sampled. With tomosynthesis, however, one can easily see that there is a portion of frequency space inside the solid cone in which no data are available. This is the cause of the failure of tomosynthesis to provide perfect 3D imaging of a 3D object.

Modified FBP provides a description of filtering that can be used in combination with backprojection to yield tomosynthesis slice images with desired properties. The following description of the generalized 3D impulse function is adapted. It is described by the following relationship:

$$G_{backproj}(\omega_x, \omega_y, \omega_z) = H_{backproj}(\omega_x, \omega_y, \omega_z) F(\omega_x, \omega_y, \omega_z) \quad \dots\dots\dots (1)$$

where $G_{backproj}$, F , and $H_{backproj}$ are the Fourier transforms of the 3D reconstructed object, the 3D object itself, and the 3D impulse function from the unfiltered backprojection process. The goal of FBP is to generate reconstructed images that better approximate the true function F . To accomplish FBP, the right-hand side of equation (1) is multiplied by an additional filtering function, H_{filter} (equation 2):

$$H_{filter} = H_{spec} H_{proj} H_{inverse} \quad (\text{modified FBP}) \quad \dots\dots\dots (2)$$

$$H_{filter} = H_{spec} H_{inverse} \quad (\text{original FBP}) \quad \dots\dots\dots (3)$$

Fig. 1 Limited sampling of 3D frequency space by tomosynthesis using linear geometry.

$$\begin{cases}
 H_{spec}(\omega_r) = 1 & \left(\text{case } \omega_r < \frac{CFR - WFR}{2} \right) \\
 H_{spec}(\omega_r) = \frac{1 - \sin(\omega_r - CFR) \cdot \pi / WFR}{2} & \left(\text{case } \frac{CFR - WFR}{2} < \omega_r < \frac{CFR + WFR}{2} \right) \\
 H_{spec}(\omega_r) = 0 & \left(\text{case } \omega_r > \frac{CFR + WFR}{2} \right)
 \end{cases}$$

$$\omega_r = \sqrt{\omega_x^2 + \omega_y^2 + \omega_z^2}$$

$$H_{prof}(\omega_z) = \exp\left(-0.693\left[\frac{\omega_z}{CFD}\right]^2\right)$$

$$H_{inverse}(\omega_R) = |\omega_R|, \quad \omega_R = \sqrt{\omega_x^2 + \omega_y^2}$$

where H_{spec} is an arbitrary filter function in the x - y orientation to modify the frequency response of reconstructed images (typically to control high-frequency noise), H_{prof} is the response function corresponding to the slice profile in the z -direction, and $H_{inverse}$ is the approximate reciprocal of the backprojection transfer function $H_{backproj}$. H_{prof} is imposed to produce as uniform a slice thickness as possible in z . The purpose of $H_{inverse}$ is to modify the response of the reconstructed image so that it does not display fall-off inversely related to that radial frequency, which is typical of the backprojection process.

In this paper, we describe a four-step process to perform this generalized filtering process on the 3D data reconstructed by simple backprojection (reference to Fig. 2)

- 1) Determine the transfer function $H_{backproj}$ of the backprojection process.
- 2) Approximate the reciprocal $H_{inverse}$ of the function $H_{backproj}$;
- 3) Design an application-specific filter function H_{filter} in the 3D spatial frequency domain, consisting of $H_{inverse}$ and the desired profile function H_{prof} and the desired x - y spatial filter function H_{spec} , and

- 4) Transfer the derived filter function H_{filter} from the 3D spatial frequency domain to the domain of 2D projection image frequency space. Perform all filtering on the 2D projection images rather than the 3D frequency domain data in order to save computation time.

1-2 Evaluation of modified FBP algorithm by Numerical Simulation Study

We performed computer simulation using a 3D Shepp-Logan phantom¹³⁾ to compare the original FBP algorithm¹⁴⁾ (equation 3) and modified the FBP algorithm¹²⁾ (equation 2). The source-to-origin distance was set to 511 mm. The number of detectors per projection was 512×512 (rectangular plane). The size of the 2D detector plane was 216×216 mm². The number of projections was 90. The numbers of radial and angular samples were 512 and 40, respectively. Each reconstructed image volume had dimensions of 216×216×216 mm³, and contained 512×512×512 voxels (Table).

1-3 Real scan for hip prostheses study

To examine the potential usefulness of digital linear tomosynthesis in replacing the standard and x-ray radiographic views, CT data were collected by using a digital linear tomosynthesis system (Sonialvision Safire, Shimadzu Corp., Kyoto, Japan). This system consists of an x-ray tube (0.4 mm focal spot) and a 432×432 mm digital flat-panel detector (1024×1024 pixels, amorphous selenium) with 421 μm pixel size. The object to be imaged is placed on a positioning stage, and views are acquired while the tube and detector are kept fixed. The digital linear tomosynthesis images were reconstructed by using a modified FBP algorithm. A data set with 90

Fig. 2 Diagram of constrained tomosynthesis shows how the projections were modified by 3D filtered backprojection(FBP)

projection images and a 40-degree tomographic angle was obtained. An x-ray technique of 70 kVp and 160 mA was used, with a 200-millisecond exposure time per view. To demonstrate the potential benefits of digital tomosynthesis compared with x-ray radiography and CT in imaging hip prostheses, an x-ray technique of 70 kVp and 200 mA was used, with a 100-millisecond exposure time per view. An x-ray radiographic system with a flat-panel detector(DigitalDiagnost, Philips Medical Systems, Hamburg, Germany) was used. The CT scans were performed on a multi-slice CT scanner(SOMATOM Sensation 16, Siemens, Forchheim, Germany) with 120 kVp, 200 mAs, 0.75 mm×16 collimation, and 0.75 second gantry rotation time at beam-pitch 0.5. Multiplanar reformations(MPR) of the CT images were compared to the tomosynthesis images.

2 . Results

In the numerical simulation, the 3D Shepp-Logan phantom was used to evaluate the proposed algorithm against an existing Feldkamp-type algorithm. Representative reconstruction results are presented in Fig. 3. It can be observed that the traditional Feldkamp-type reconstruction suffered from significant intensity dropping away from the mid-plane, which is a well-known drawback of the original FBP algorithm. On the other hand, our modified FBP algorithm improved the image quality remarkably, providing better image quality than the original FBP algorithm. Specifically, the modified FBP algorithm suppressed the artifacts very well, even for a fairly larger-than-cone angle, which is several times larger than that with the traditional Feldkamp-type reconstruction for similar image quality(Figs. 3-5)

The hip prosthesis is clearly depicted in an antero-posterior(AP) view radiograph(Fig. 6) In comparison,

Table Computer simulation parameters for the voxelized 3D Shepp-Logan phantom.

Object	Value
Source trajectory radius	511 mm
Source to detector	1024 mm
Number of projection	90 projections
Detector number	512×512
Detector cell size(height×width)	216×216 mm ²
Reconstruction grid(voxel size)	512×512×512
Trajectory linear	linear(40 degrees)

digital linear tomosynthesis images yielded of this hip prostheses 3D information. On the digital linear tomosynthesis images, the hip prostheses that lay outside the reconstruction plane were blurred, as shown Fig. 7. The difficulty of discerning structures in a radiographic image of the hip prosthesis as a result of the presence of overlying structures is evident in a radiograph. The use of digital linear tomosynthesis improved visualization of the underlying tissue detail by blurring the overlying structures. CT provided information(MPR of images) about the hip prostheses, as shown in Fig. 8. The MPR of CT images suffers from string artifacts in every region. In addition, due to strong beam hardening and scatter effects, the region of the femur is poorly displayed. The hip prostheses that are present in the CT images are effectively removed by the blurring in the 90-projection digital linear tomosynthesis image. This allows better visualization of the tissue detail directly below the hip prostheses structures in complex.

3 . Discussion

Digital linear tomosynthesis provided adequate overall performance, but it was obvious that its effectiveness strongly depends on the region of the image. Digital linear tomosynthesis images give good results independent of the type of metal present in the patient, and show good results for the removal of noise artifacts, especially at greater distances from metal objects. The application of digital linear tomosynthesis to the imaging of hip prostheses appears promising. The 3D visualization of hip joints on digital linear tomosynthesis images is far superior to that on a standard AP radiograph(Figs. 6, 8) In addition, the flexibility in the choice of digital linear tomosynthesis imaging parameters based on the desired final images and realistic imaging conditions may be beneficial.

CT images of the artifacts, which depend on numer-

Fig. 3 Reconstruction simulation images of the 3D Shepp-Logan phantom at different heights.

Fig. 4 Comparison of axial profile plots through the reconstructed 3D image function in comparison with the discretization of the 3D Shepp-Logan phantom. (center plane)

Fig. 5 Comparison of axial profile plots through the reconstructed 3D image function in comparison with the discretization of the 3D Shepp-Logan phantom (off-center plane)

Fig. 6 Anteroposterior (AP) radiograph of hip prosthesis demonstrates the hip joint with this view.

Fig. 7 Tomosynthesis images of a hip prosthesis at different heights. The level is the same as in Figs. 6 and 8 (40° tomographic angle, with 90 views) The reduction in the number of artifacts in the images was obtained with show view.

Fig. 8 Coronal slice images of a hip prosthesis at different heights from a CT scan at approximately the same level as in Figs. 6 and 7 (MPR of images; 3 mm slice, 3 mm interval)

ous factors such as size, shape, density, atomic number and position of the metal objects, patient size, and the shape of the patient's cross section. Especially for small implants manufactured from relatively light metals (e.g., titanium), the impact of beam hardening and scatter effects is low, so that corrupted CT values can be neglected, and noise-induced streaking artifacts pose the main problem to image quality. In these cases, digital linear tomosynthesis approaches should be perfected. This would appear to be promising for the reduction of artifacts stemming from metals with a relatively high atomic number (Figs. 7, 8).

The digital tomosynthesis images in this study were acquired by using linear motion of the x-ray tube and detector. The type of motion used during data acquisition dictates the type of blurring of off-focal-plane objects in the image. Linear motion blurs objects in one dimension only, which leads to linear streak artifacts caused by high-contrast off-focal-plane objects.

An alternative approach to tomosynthesis imaging is to determine the number of views that can be acquired given imaging constraints (e.g., time restrictions from patient motion, dose restrictions of the detector). The tomographic angle can be selected to yield images with an acceptable number of artifacts; the tomographic angle then determines the achievable section thickness. It appears that the number of views required for visualiz-

ing hip prostheses is quite large because of the complex structures present in this region. This is certainly the case with our modified FBP algorithm, as indicated in this report, and would also be the case with simple backprojection (or a shift-and-add algorithm). It is possible, however, that this restriction could be lessened by the use of an alternative reconstruction scheme. We have limited our evaluation of digital linear tomosynthesis reconstruction schemes to back projection, but other techniques such as iterative reconstruction should be examined if the current techniques prove too limiting for clinical application.

4. Conclusion

In summary, the use of digital linear tomosynthesis in the imaging of hip prostheses appears promising. Results of hip joint experiments suggest that digital linear tomosynthesis can improve image quality compared with conventional radiography by removing overlying structures and providing limited 3D information. In addition, the digital linear tomosynthesis method appears to allow for a significant improvement of images that are corrupted by metal artifacts. The image information of digital linear tomosynthesis was shown to provide high-quality images compared to CT images. In addition, we presented the result that clinical evaluation used a limited case and performed for a trial.

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図表の説明

- Fig. 1 直線軌道を使ったトモシンセシスによる投影サンプリング(実空間)の三次元フーリエ空間
- Fig. 2 三次元フィルタ補正逆投影法(修正バージョン)の概要. 投影データからの再構成方法の概要をブロック図で示す.
- Fig. 3 3D Shepp-Logan ファントムを用いたシミュレーションによる, 異なる位置(z方向)の再構成画像の結果
- Fig. 4 3D Shepp-Loganファントムによる回転中心面での再構成画像の垂直方向プロファイル(画像の中心位置)の比較
- Fig. 5 3D Shepp-Loganファントムによる回転中心面より7cm上方の再構成画像の垂直方向プロファイル(画像の中心位置)の比較
- Fig. 6 股関節の人工関節置換術を施行した単純X線写真
- Fig. 7 Fig. 6, 8と同一患者で, 異なる再構成面(z方向)を表示したデジタルトモシンセシスの画像(断層角40度, 投影数90). 大幅にアーチファクトが低減されているのが確認できる.
- Fig. 8 Fig. 6, 7と同一患者のCT画像. 提示した画像は, MPRを用いた多断面表示(coronal面, 3mmスライス厚, 3mm再構成間隔).
- Table 3D Shepp-Loganファントムを用いてコンピュータシミュレーションを施行したときの設定パラメータ