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Limited Angle Tomography

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1. Introduction

In computed tomography (CT), many situations are restricted to obtain enough number of projections or views to avoid artifacts such as streaking and geometrical distortion in the reconstructed images. Speed of motion of an object to be imaged can limit the number of views. Cardiovascular imaging is a representative example. Size of an object can also limit the complete traverse motion or geometrical complexity can obscure to be imaged at certain range of angles. These situations are frequently met in industrial non-destructive testing and evaluation. Dental CT also suffers from similar situation because cervical spine causes less x-ray penetration from some directions such that the available information is not sufficient for standard reconstruction algorithms.

The limited angle tomography is now greatly paid attention as a new genre in medical and industrial imaging, popularly known as *digital tomosynthesis* [1]. In this study, we introduce a modified filtered backprojection method in limited angle tomography and demonstrate its application for the dental imaging.

2. Theoretical Framework

We briefly describe in this section a theory of a filtered backprojection method in limited angle tomography employing isocentric motion. Important assumptions underlined in this theory are parallel beam geometry, continuous sampling and linear process of projection-backprojection operation. The theoretical framework is mostly based on the work of Lauritsch and Haerer [2], that reported a filtered backprojection in circular motion digital tomosynthesis.

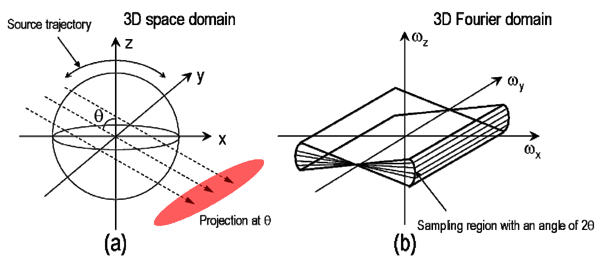

Figure 1. Illustration of the Fourier-slice theorem and incompleteness of object information in limited angle tomography. Projection data set in the space domain (a) is mapped into the Fourier domain (b) in a double-wedge shape. Only the double-wedge shaped data in the Fourier domain are sampled.

Three dimensionally (3D) reconstructed image $g(x, y, z)$ can be described by a convolution of an object $f(x, y, z)$ with the 3D point spread function $h(x, y, z)$;

$$g(x,y,z) = h(x,y,z) \otimes_3 f(x,y,z), \qquad (1)$$

where $\otimes_3$ designates a 3D convolution. In Fourier domain, Eq. (1) can be written as

$$G(\omega_x,\omega_y,\omega_z) = H(\omega_x,\omega_y,\omega_z)\cdot F(\omega_x,\omega_y,\omega_z), \qquad (2)$$

where all the characters and symbols are the corresponding Fourier conjugates of those described in Eq. (1). H is the transfer function or impulse response function of the operation of projection and backprojection in computed tomography. Then we can determine the object function by

$$\begin{aligned} f(x,y,z) &= \mathbf{FT}_3^{-1}\left[\frac{G(\omega_x,\omega_y,\omega_z)}{H(\omega_x,\omega_y,\omega_z)}\right] \\ &= \mathbf{FT}_3^{-1}\left[H^{-1}(\omega_x,\omega_y,\omega_z)\cdot G(\omega_x,\omega_y,\omega_z)\right] \end{aligned}, \qquad (3)$$

where $\mathbf{FT}_3^{-1}$ indicates a 3D inverse Fourier transform.

From the Fourier-slice theorem, projections from all angles in 3D space are needed to reconstruct the original object function f. However, since in limited angle tomography or digital tomosynthesis for isocentric motion, a parallel beam projection samples object information on a plane perpendicular to the projection data [2], the sampled information consists of only a double wedge in Fourier space as shown in Fig. 1. For the isocentric sampling scan in x-direction with a half of limited angle, θ around the axis of rotation, y [3],

$$H^{-1}(\omega_x,\omega_y,\omega_z) = H_{inv}(\omega_x,\omega_z) = 2\alpha\sqrt{\omega_x^2+\omega_z^2}. \qquad (4)$$

This is a ramp filter typically encountered in CT. The ramp filter is vulnerable to high-frequency noise that could be suppressed by an appropriate spectral filter, $H_{spectrum}$. In this study, we use a Hanning window.

As shown in Fig. 1, Eq. (4) becomes infinite in the incomplete region ($|\omega_z| > |\omega_x|\tan\theta$), which implies a step function in ω_z-direction sampling in the Fourier space. This discontinuity in the sampling would be appeared as a ringing artifact and also increase the out-of-plane artifact. This behavior could be suppressed by an additional filtering operation that may be achieved in a similar way as the spectral filter. This slice profile filter, $H_{profile}$, ensures a constant depth resolution over a wide range of spatial frequencies.

Key procedure in the filtered backprojection for the limited angle tomography is therefore to determine

$$H^{-1}(\omega_x,\omega_y,\omega_z) = H_{inv}(\omega_x,\omega_z)\cdot H_{spectrum}(\omega_x)\cdot H_{profile}(\omega_z) \quad (5)$$

Essential procedure in the evaluation of Eq. (5) is to find adjustable filter parameters, *i.e*. cutoff frequencies, related to the spectral and slice profile filters.

3. Experimental

In order to test the reconstruction algorithm introduced in the previous section, we obtained projection data in CT motion from the self-developed miniaturized CT system [4]. The sample was an extracted human tooth. For the limited angle tomography situation, we took partial data in the obtained full scan data.

For the clinical implementation in dental imaging, we applied the algorithm to the commercial dental CT system (Implagraphy^{TM}, Vatech). The experiment was performed with a human skull phantom.

4. Results and Discussion

Figure 2 shows the reconstructed human tooth. The reconstruction was performed with 11 views for 2θ = 100°. The magnification ratio was 2. The image size is 512 × 512 × 1 voxels and the voxel size is (96 μm)^3. In this case, only the spectrum filter with a parameter of 0.5 times of the cutoff frequency, *i.e*. $0.5\omega_{Ny}$, was considered. For the comparison, the image obtained by the simple backprojection method, which is the most common shift-and-add method in digital tomosynthesis, is shown in Fig. 2(b) and that obtained by the FDK method [5] in Fig. 2(c). As demonstrated, the image quality obtained by the filtered backprojection method [see Fig. 2(a)] introduced in this study is the best.

The reconstructed image obtained from the commercial system is demonstrated in Fig. 3. The magnification factor was 1.6. The image size is 512 × 512 × 1 voxels and the voxel size is 200 × 200 × 500 μm^3. The parameters of the spectral and the profile filters were $1.5\omega_{Ny}$ and $0.7\omega_{Ny}$, respectively. Figure 3(a) and (b) were obtained with 49 views for 2θ = 28° and with 25 views for 2θ = 56°, respectively. Unlike the single tooth, this demonstration needed more views, which is due to the structural complexity of the skull phantom. However, the number of views used is still much smaller than that typically used in the conventional CT and the quality is very promising.

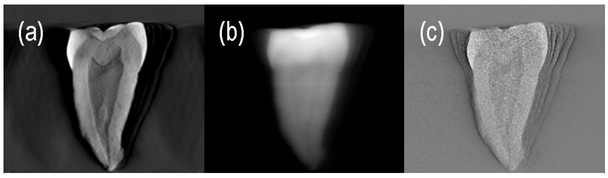

Figure 2. (a) An illustrative tomogram obtained by the filtered backprojection method described in this study for an extracted human tooth. For the comparison, tomograms obtained by using the SAA method (b) and the FDK method (c) are also shown.

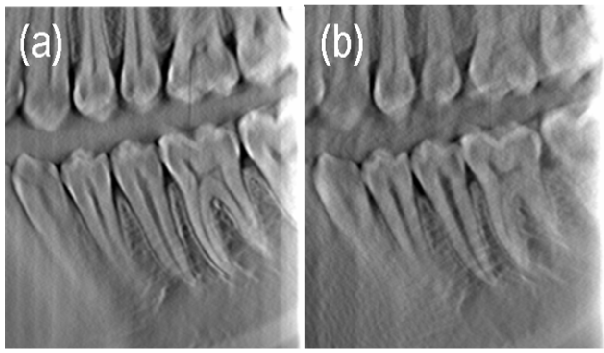

Figure 3. Tomograms obtained from the commercial dental CT system incorporating the developed filtered backprojection method for a human skull phantom. (a) was obtained with 49 views for 2θ = 28° and (b) with 25 views for 2θ = 56°.

5. Conclusion

We described a filtered backprojection method for the limited angle tomography and demonstrated its usefulness in dental imaging. The digital tomosynthesis for the dental imaging has a potential to be used for planning an implant procedure with much reduced patient dose instead of the conventional dental CT. For the better use of the filtered backprojection method, the optimization of filter functions is needed. Development of true cone-beam geometry instead of parallel-beam approximation is left as a future work.

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