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Measurement of spatial resolution of the micro-CT system*

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Abstract The performance test is an important and necessary work for the micro-CT (computed tomography) system. The focal spot size of the micro focus X-ray tube is measured. The method of measuring the spatial resolution of micro-CT is introduced. A line-pair resolution of 28.2 lp/mm at the 10% modulation transfer function (MTF) level can be achieved with 14.7 μm spot size, 12.3 μm voxel size and a 25 mm field of view. In addition, a tungsten wire with the diameter of 5 μm can be detected by the system.

Key words micro-CT, line-pair resolution, MTF

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1 Introduction

The technology of CT (computed tomography) has been developed in medical and industrial fields for many years [1–3] Recently, micro-computed tomography (micro-CT) systems are becoming more common in these fields in research laboratories or companies [4–6], due to their ability to achieve spatial resolution as high as several microns, giving highly detailed anatomical information. Micro-CT uses micro focus radial source to ensure high level resolution. It once uses synchrotron radiation source [7]. Corrently Micro-CT systems with X-ray tube are the popular products because they are more flexible and easier to extend in many cases.

For paleontology research, CT is a newly introduced technique. In the year of 2007, a joint project on paleontology studies by three institutes of Chinese Academy of Sciences (CAS) was approved. The project includes the development of two scientific equipments, called 450 kV universal ICT and 225 kV-3D-micro ICT respectively. The 225 kV-3D-micro ICT is a cone-beam micro-CT mainly for scanning middle or small amniotes to get the tomogram of their subtle organs and inner structures which are super fine. The 3D reconstruction of the scanned objects can be made and it is convenient for the researchers to study the scientific problems. At the moment of accomplishing the project, we tested the spatial resolution of the 225 kV-3D-micro ICT system. In this paper, we will introduce the methods of measuring the focal spot size and the spatial resolution. Then, after measuring the spot size of the X-ray tube, the spatial resolution of the system is to be presented.

2 Methods of measurement

In our system, one micro focus X-ray tube of FXE225.99 from COMET and a flat panel detector of Varian PaxScan® 4030CB with 194 μm pixel size and 2048×1536 pixels were utilized.

2.1 The method of measuring the spot size

According to the geometrical considerations between the focal spot size and the radiographic resolution of line gratings, it can be shown that sufficiently enlarged line structures can be resolved only if the radiation source is smaller than the period of the regular grating. The inverse of the period is usually denoted as the spatial frequency in 1/mm or lp/mm (line pairs

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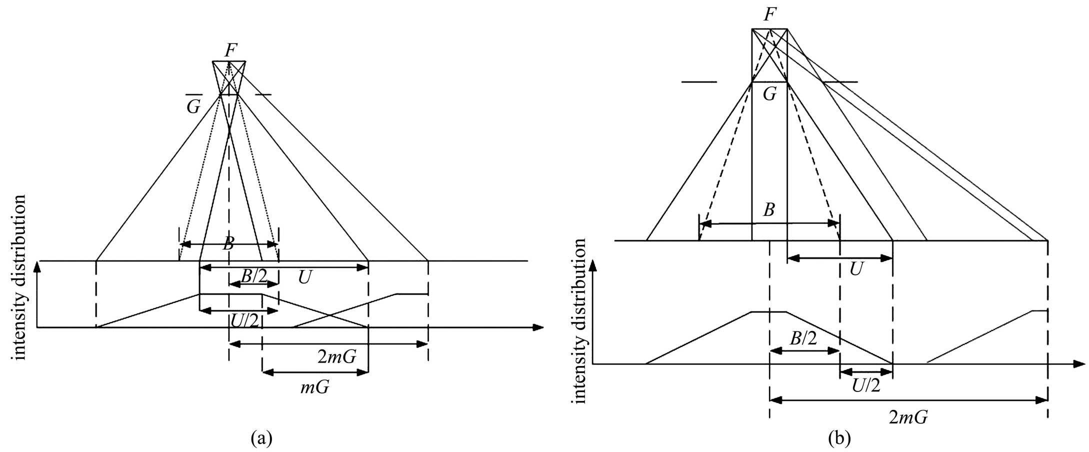

Fig. 1. Geometrical relationship between the spot size and the line grating. (a) The spot size is more than the period of the line grating ($2G$); (b) The size of spot is no more than half of the period. F is the size of the focal spot and $2G$ is the period of the line grating. B and U are the projections of half period and unsharpness of the grating respectively. The magnification is denoted as m.

per millimeter) of the line pattern.

The line grating was projected on the receptor and a map of periodical pattern formed which looked like a wave. We define the difference between the peak and trough of the wave intensity as contrast. According to the geometrical relationship as shown in Fig. 1(a), Eqs. (1) and (2) are satisfied as the following. When the contrast of the line structure decreases to zero, Eq. (3) is satisfied. We substituted (1) and (2) to (3), then when $m \to \infty$, $F \geqslant 2G$ was obtained. That is to say, when the spot size is more than or equal to the line period, the contrast decreases to zero. Conversely, we can deduce the spot size according to this point. In addition, we can obtain Eq. (4) when the line structure is separated entirely, as shown in Fig. 1(b). It is easy to prove $F \leqslant G$ at $m \to \infty$ here.

$$B = mG, \tag{1}$$

$$U = (m-1)F, \tag{2}$$

$$2mG \leqslant 2(U/2 - B/2) + mG, \tag{3}$$

$$2mG \geqslant 2(B/2 + U/2). \tag{4}$$

Usually, we can plot the amplitudes to the corresponding spatial frequency which is called modulation transfer function (MTF). The amplitudes can be substituted by relative amplitudes to the zero-frequency amplitude. We can obtain the spot size through the spatial frequency when MTF value is 10%.

2.2 The method of measuring spatial resolution

The spatial resolution of the micro-CT system is determined by the spot size S, the detector pixel size d and the geometrical magnification M. It can be described as the effective beam width [8].

$$BW = \frac{\sqrt{(S(M-1))^2 + d^2}}{M}, \tag{5}$$

$1/BW$ is called cut-off frequency which reflects the ultimate resolution with the unit of lp/mm. In practical applications, the spatial resolution will be affected by the reconstruction methods, the statistical noise, the number of projections and so on. So in order to denote the differences between the ultimate resolution and the actual resolution, we introduce c as a factor for adjustment. The line-pair number LPN can be shown as Eq. (6).

$$LPN = 1/(BW \times c), \tag{6}$$

The LPN can be quantified by a measurement of the line-spread function (LSF) of the system or equivalently, by the modulation transfer function, the frequency-space representation of the LSF [9]. MTF is determined by computing the amplitude of the Fourier transform of the LSF. The LSF is obtained by calculating the derivative of the profile of the edge of the cylindrical test phantom which is called edge response function (ERF).

3 Experimental results

3.1 The results of spot size measurement

A micro-chart (Fig. 2) produced by JIMA (Japan Inspection Instruments Manufacturers' Association) [10] was used as the line gratings. It was attached in the front window of the X-ray tube. The tube voltage of 160 kV was applied and the tube power was nearly

15 W. The magnification was about 170.0 which is large enough for the imaging.

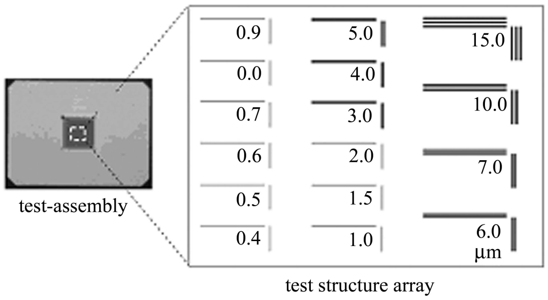

Fig. 2. The line gratings produced by JIMA. Half periods of different line gratings are given.

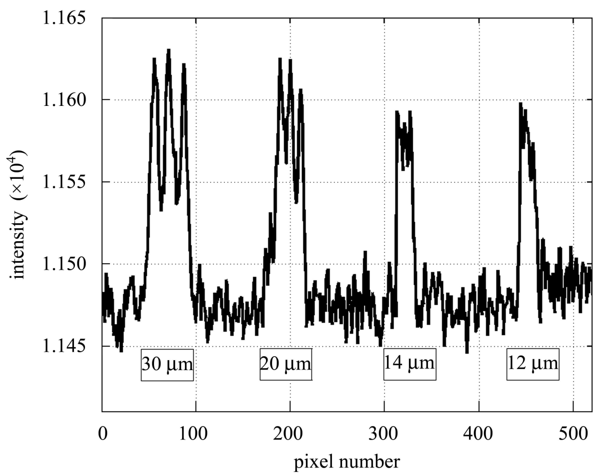

Fig. 3. Cross section of different line gratings' projections.

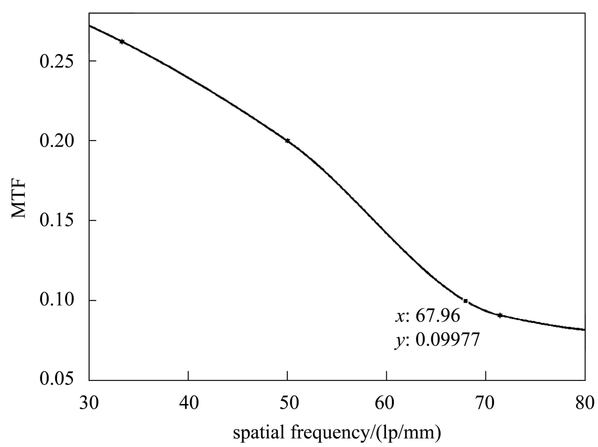

Fig. 4. Modulation transfer function of the line pattern.

Figure 3 shows the cross section of different line gratings. The periods of the line gratings are also signed in the figure. In the process of MTF, zero-frequency amplitude was defined as the difference between the max value and the average background. From Fig. 4, a spatial frequency of 68.0 lp/mm at MTF-value of 10% could be reached for the focal spot, which meant an effective size of 14.7 μm.

3.2 The results of the spatial resolution measuring

A test phantom of aluminium cylinder with 20 mm diameter was scanned in our system at a magnification of 15.7 and 25 mm field of view (FOV). The voltage of the X-ray tube was fixed at 160 kV and the power was 15 W. The phantom was set nearly at the center of FOV. It was reconstructed with the Feldkamp (FDK) [11] algorithm with Ram-Lak filter in a 2048×2048 matrix. The ERF (Fig. 6) and LSF (Fig. 7) were calculated based on the reconstruction image (Fig. 5). The MTF (Fig. 8) of the system was obtained finally from the PSF. During the process of the ERF, we averaged many edge profiles of the phantom reconstruction image.

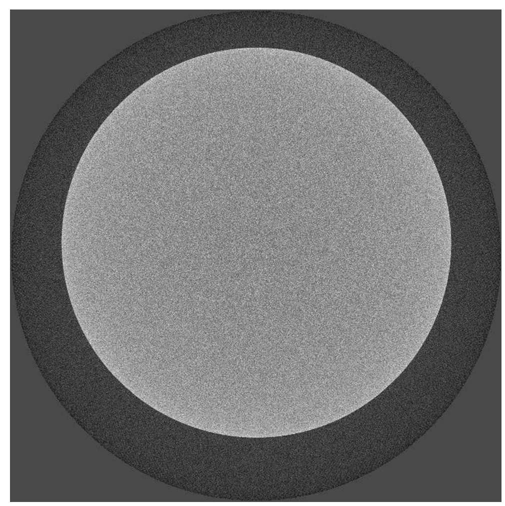

Fig. 5. Slice reconstruction of the aluminium column.

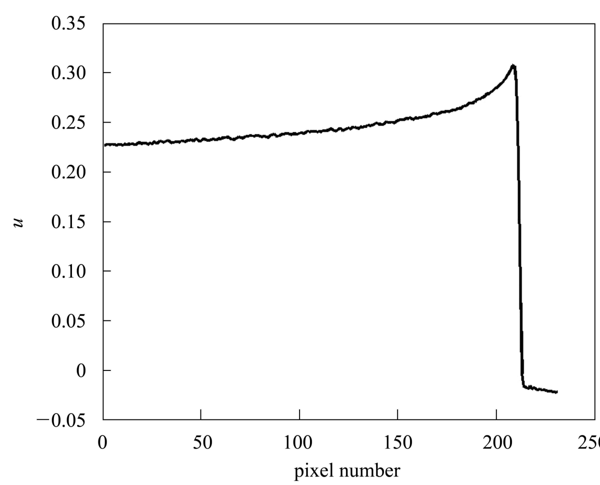

Fig. 6. The edge response function of the system.

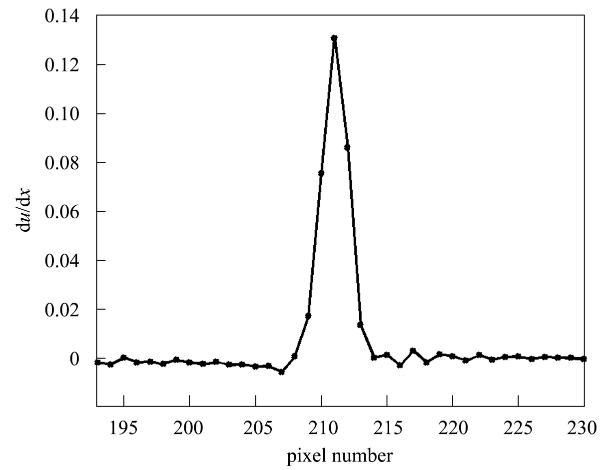

Fig. 7. The system line-spread function.

Figure 8 demonstrates that a resolution of 28.2 lp/mm at the 10% MTF can be achieved. The focal spot size was 14.7 μm. We used Eq. (5) to get $1/BW$'s value which was 54.1 lp/mm. According to Eq. (6), we got c=1.9.

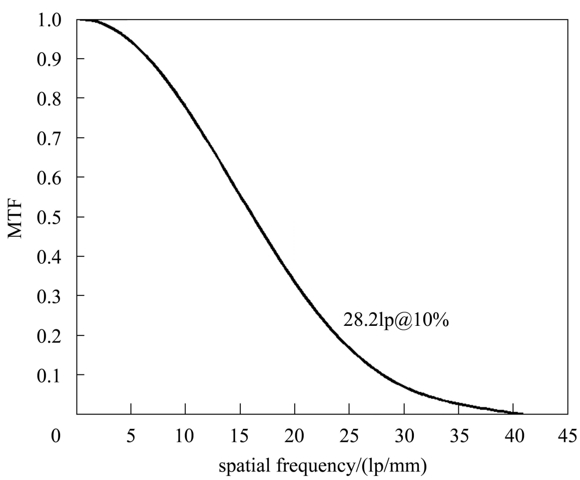

Fig. 8. The system modulation transfer function.

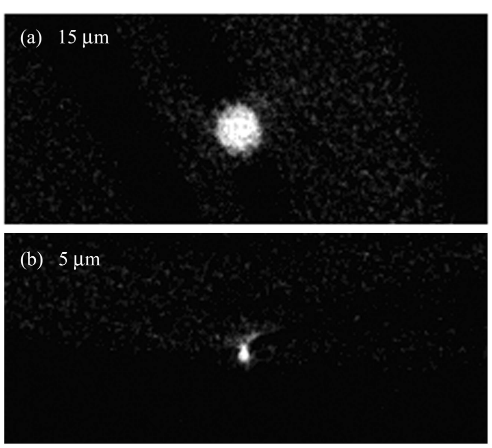

Fig. 9. Cross sections of 15 μm gold-filled tungsten wire (a) and a 5 μm tungsten wire (b).

A sample composed of a 15 μm diameter gold-filled tungsten wire and a 5 μm tungsten wire was also scanned. The two wires were adhered to an underprop by an adhesive tape. Fig. 9 shows cross sections of the wires. They were surrounded by adhesive tape or air. Fig. 10 shows the line including two wires. To be seen clearly, they were drawn in one plot.

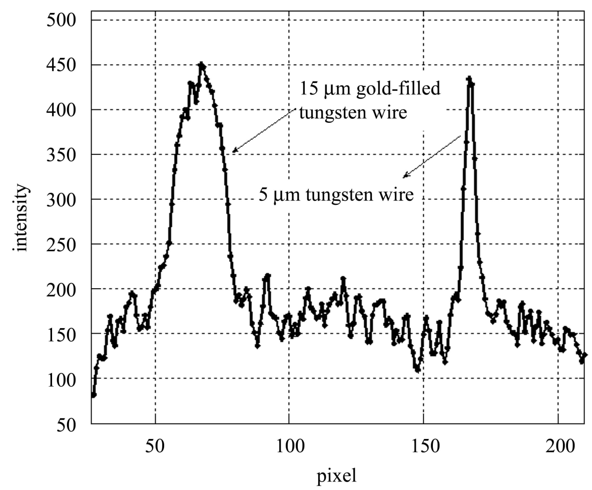

Fig. 10. The line including the two wires.

3.3 The influence of filters on the spatial resolution

For the FDK algorithm, different filters represent different responses of the spatial frequency. As a result, spatial resolution was affected seriously by the chosen filter. Fig. 11 demonstrates the MTF from the same aluminium phantom as above in different filters. Fig. 12 shows the ability of different filters' response to different frequencies. The spatial resolutions at 10% MTF value for different filters are shown in Table 1.

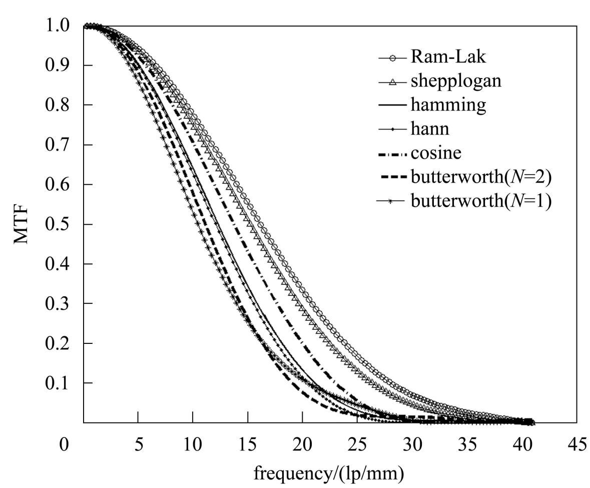

Fig. 11. The MTF in different filters.

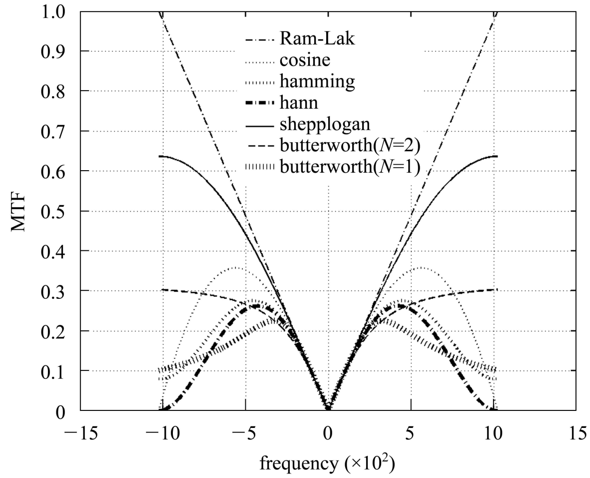

Fig. 12. The response ability of different filters.

We can see that Ram-Lak filter is best at high frequency and Butterworth ($N=2$) is the worst. Moreover, spatial resolutions are different in different materials. At the same time, the projection number is another influence factor [12].

4 Summary

The spot size was measured in our experiment at 160 kV voltage and 15 W tube power. A line pair resolution of 28.2 lp/mm at the 10% modulation transfer function level can be achieved with a 14.7 μm spot size, 12.3 μm voxel size and a 25 mm field of view. Meanwhile, a 5 μm tungsten wire can be distinguished by the system. More methods to improve the spatial resolution are under research. A detailed description about these will be given in the future.

Table 1. Line pairs @10% MTF.

filters	Ram-Lak	SheppLogan	cosine	hamming	hann	butterworth ($N=1$)	butterworth ($N=2$)
line-pair number (10%MTF)	28.2	26.3	23.1	21.2	20. 6	22.8	19.0

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References

1 Hounsfield G N. British Journal of Radiology, 1973, **46**: 1016–1022
2 Sweency D W. Radiation Gage Imaging for Nondestructive Testing Applications LLL Univ California. UCRL-51641.1974
3 Kruger R P, London J R. Mater Eval, 1982, **40**: 1285–1289
4 http://www.gehealthcare.com/usen/fun_img/pcimaging/products/microctscanner.html
5 http://www.skyscan.be/products/all_products.htm
6 http://www.xradia.com/
7 Spanne P, Rivers M. Nucl. Instrum. Methods Phys. Res. B, 1987, **24/25**: 1063–1067
8 Yester M W, Barnes G T. Proc. SPIE, 1977, **127**: 296–303
9 ASTM International. Standard Test Method for Measurement of Computed Tomography (CT) System Performance. E1441-00: 16
10 http://jima.jp/content/pdf/rt_ct-02cata02.pdf
11 Feldcamp L A, Davis L C, Kress J W. J. Opt. Soc. Am., 1984, **1**(6): 612–619
12 Joseph P M, Schulz R A. Medical Physics, 1980, **7**(6): 692–703