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The effect of focal spot size on the spatial resolution of variable resolution X-ray CT scanner

H. Arabi, A.R. Kamali Asl*, S.M. Aghamiri

Radiation Medicine Department, Shahid Beheshti University, Tehran, Iran

Background: A variable resolution X-ray (VRX) CT scanner provides a great increase in the spatial resolution. In VRX CT scanners, the spatial resolution of the system and its field of view (FOV) can be changed according to the object size. One of the main factors that limit the spatial resolution of VRX CT scanner is the effect of the X-ray focal spot. ***Materials and Methods:*** A theoretical study of the effect of X-ray focal spot on the spatial resolution of VRX CT is presented in this paper. In this study, we used the parameters of an actual VRX CT scanner. By using the relevant equations, the effects of foal spot sizes of 0.6 and 0.1 mm were calculated on spatial resolution of the system at various opening half angles. ***Results:*** Focal spot size of 0.6 mm had no significant effect on spatial resolution of the system for opening half angles of above 14°. Even focal spot sizes of larger than 0.6 mm could not affect the spatial resolution of the system. For opening half angles of below 14°, foal spot size of 0.6 mm limited the spatial resolution of the system to 5.7 cycle/mm and caused great spatial resolution non-uniformity along the detector length. ***Conclusion:*** By focal spot size of 0.1 mm, the spatial resolution varied as a function of the opening half angle and increased to more than 30 cycle/mm. Additionally, focal spot size of 0.1 mm minimized the spatial resolution non-uniformity along the detector length. **Iran. J. Radiat. Res., 2010; 8 (1): 37-43**

Keywords: *Variable resolution X-ray (VRX) CT scanner, focal spot size, spatial resolution.*

INTRODUCTION

Computed tomography (CT) is a powerful method of diagnostic imaging. It can provide three-dimensional and high contrast images of *in vivo* anatomy. Generally, we can divide CT scanners in two main categories: clinical CT and micro-CT scanner. Clinical CT scanners have large field of view (FOV) of 40-50 cm that is more appropriate for whole-body imaging. Their spatial resolution is only 2-3 cycle/mm [1, 2]. Decreasing the object size has no effect on spatial resolution of clinical CT scanners, large and small objects are imaged at the same spatial resolution. On the other hand, micro-CT scanners provide high spatial resolution of up to 100 cycle/mm and only FOV of a few centimeters [2, 3].

Despite great progress in image quality of CT scanners, there is still a growing demand for the improvement of the spatial resolution. A CT scanner that can provide the advantages of both clinical CT and micro-CT scanners is highly desirable. Variable resolution X-ray (VRX) CT scanner introduces a method in that spatial resolution of the system is changed according to the object size [4, 5]. The idea to increase the spatial resolution in this CT scanner is angulation of the detector with respect to the incident X-ray beam. By angulation of the detector, the apparent cells size in object plane becomes smaller than their physical size and consequently the spatial resolution of the system will change as a function of the angulation angle. The FOV of VRX CT scanner is also variable and a function of the detector angulation angle.

High spatial resolution (more than 40 cycle/mm) is achieved at small detector angulation angles but FOV of the system decreases (1 cm) at small angles. On the contrary, at large detector angulation angles spatial resolution is minimum (1-2 cycle/mm) but FOV of VRX CT scanner reaches its maximum (40 cm) [6]. Thus, small objects

****Corresponding author:***
Dr. Ali Reza Kamali Asl,
Radiation Medicine Department, Shahid Beheshti University, Tehran, Iran.
Fax: *+98 21 22431780*
E-mail: *A_R_Kamali@yahoo.com*

are imaged at high spatial resolution with small FOV and large objects are imaged at low spatial resolution with large FOV.

VRX CT scanner is in its early state. Most of studies on this system were concentrated mostly on feasibility of this method and improving the major factors of imaging (7-9). The novel idea of angulations' of detector to improve the spatial resolution is applicable for variety of configurations. Every configuration has its own features and limitations that needs separate investigation like four-arm and flat panel VRX detectors (10-12).

The limitation due to the effect of X-ray focal spot size is a common problem to all VRX CT scanners. One of the main factors that limit the spatial resolution in VRX CT scanners is geometrical unsharpness due to focal spot size. By angulations' of the detector, the spatial resolution improvement is due to increase in detector resolution but the influence of geometrical unsharpness due to the focal spot remains constant. To reach acceptable spatial resolution in VRX CT systems, the limiting effect of focal spot on spatial resolution should be precisely studied. To fulfill this aim, we used the numerical values of parameters of an actual VRX CT scanner to theoretically study the effect of focal spot size on spatial resolution of the system. In actual VRX CT scanner, the focal spot size is 0.6 mm that limited the spatial resolution of the system to 5.7 cycle/mm and also caused great resolution non-uniformity along the detector length. By focal spot size of 0.1 mm, the spatial resolution rose more than 30 cycle/mm and also minimized the resolution non-uniformity along the detector length.

MATERIALS AND METHODS

VRX CT scanner

A schematic diagram of a typical VRX CT scanner is depicted in figure 1. A dual-arm VRX detector was preferable because of its left-right symmetry and lower magnification non-uniformity from one end of the detector to the other (13, 14). The two detector arms rotate around the common pivotal point (Vertex). By reducing the opening half angle (α), the apparent cell's size became smaller than its physical size in the object plane, and consequently, the spatial resolution of the system increased. The FOV of the system (FOV circle in figure 1) decreased as the opening half angle was reduced (6). X-ray source was placed at the distance of SVD (source-vertex distance) from the vertex of the detector, the SOD (source –object distance) showed the distance between the X-ray source and center of the FOV circle, and the θ is the incident angle.

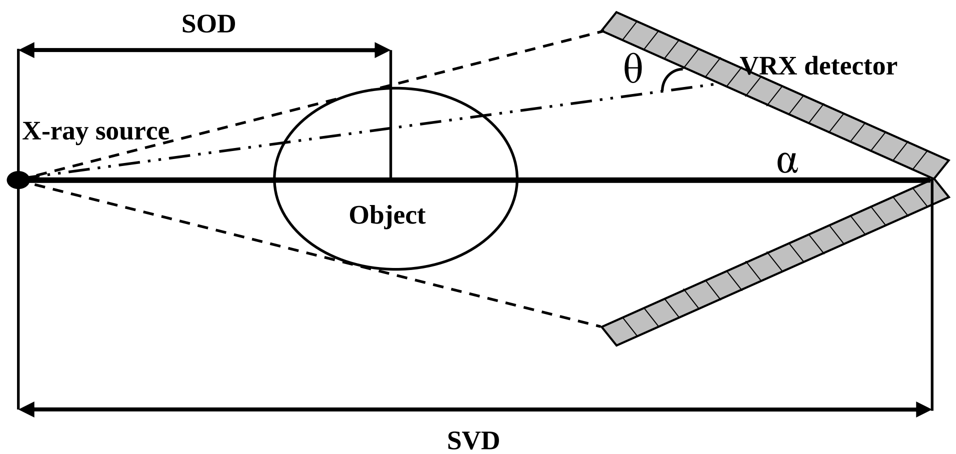

Figure1. Schematic diagram of a VRX CT scanner: SVD source-vertex distance, SOD source-object distance, θ incident angle, α is opening half angle (6).

Theory

The detector elements size and X-ray focal spot size are the main factors, which determine the spatial resolution of any X-ray imaging system. In theory, the spatial resolution of the system can be calculated separately for detector resolution and the X-ray focal spot unsharpness. The detector resolution is defined as the projected width of detector cells on object plane while other contributory factors are assumed ideal. The width of the detector cells and the system magnification determine the sampling width in object plane by detector.

$$U_D = \frac{M}{W} \quad (15) \qquad (1)$$

U_D is the detector resolution when the width of the detector cells is W and the system magnification if M.

Similarly, the resolution of the system due to the X-ray focal spot unsharpness, is the projected width of the X-ray focal spot on object plane.

$$U_s = \frac{M}{A(M-1)} \quad (15) \qquad (2)$$

U_S is the spatial resolution of the system only by influence of the X-ray focal spot where A is focal spot size and the M is the system magnification. Equations 1 and 2 define the portion of each of detector resolution and focal spot unsharpness in spatial resolution of the system. The minimum value of U_S or U_D determines the overall spatial resolution of the system and also which factor (cell's width or focal spot size) limits the spatial resolution of the system.

In VRX CT scanner, variable resolution is achieved by angulation of the detector and consequently decrease in apparent cells width. Therefore, in equation 1 the width of the detector cells (W) is not constant and changes as a function of the incident angle (θ). The detector resolution for VRX CT scanner is determined by equation 3.

$$U_\theta = \frac{M}{W \times \sin(\theta)} \qquad (3)$$

The non-uniformity of magnification is another feature of VRX detector. Since VRX detector is angulated, the distance between X-ray source and detector is different for each cell. This magnification non-uniformity causes different detector resolution for detector cells at the same opening half angle. The X-ray focal spot resolution is not also uniform for VRX detector cells because the system magnification (M) is not the same for all the cells. The magnification non -uniformity causes great different in the system spatial resolution along the detector length.

In this paper a qualitative study of effect of focal spot size on spatial resolution of a VRX CT scanner was conducted. To fulfill this aim, we used the parameters an actual VRX CT scanner designed and built by Melnyk *et al.* [6]. The former study on this VRX CT scanner has been specifically conducted on the detector resolution. In this study, we investigate how focal spot size limits the spatial resolution of the VRX CT scanner at different opening half angles. Table 1 presents the main numerical values of parameters of the VRX CT scanner. By using the geometrical parameters of the VRX CT scanner and the mentioned equations, the spatial resolution of the system with foal spot size of 0.6 mm and the influence of magnification non-uniformity along the detector length on resolution of the system were computed. We used MATLAB software for our calculations. Then the calculations were repeated by focal spot size of 0.1 mm for investigation of spatial resolution improvement.

RESULTS

Table 2 provides results of practical measurements and our study results for validation of the theoretical calculation.

Table 1. The numerical values of parameters of the VRX CT scanner [6].

Number of active cells per arm	256
Cell width (Cadmium tungstate crystal)	0.79 mm
Inner separator width (Lead separator between cells)	0.10 mm
Reflective paint width (between cells and separators)	0.05 mm
Source-vertex distance	150 cm
Source-object distance	106 cm
Active arm length	25.617 cm
Focal spot size	0.6 mm

Table 2. Comparison of findings in practical [6] and present study.

Angle	Practical results Spatial resolution (cycle/mm)	Present study Spatial resolution (cycle/mm)
62.09° (Cell 256)	1.37	1.45
26.22° (Cell 256)	2.7	2.8
21.91° (cell 1)	3.3	3.6
12.76° (Cell 256)	5.3	5.4
6.34° (Cell 256)	11	11.1

The system magnification is common in equation 1 and 2. By depicting them as a function of system magnification (M), the trend of focal spot and detector resolution was obtained for various system magnifications (figure 2). In VRX CT scanner the detector resolution increased as the opening half angle (α) decreased. Figure 2 shows the VRX detector resolution for opening half angles of 9° to 90° at different magnification. At each specific magnification, lower value of focal spot or detector resolution determined the spatial resolution of the system. There was a magnification trade-off between the detector and focal spot resolution. The crossing points of detector and focal spot resolution in figure 2 are the optimum magnification at each opening half angle. If the system magnification is set at optimum magnification, the maximum spatial resolution would be obtained at each opening half angle. By increasing the system magnification, the limiting effect of focal spot size increased on spatial resolution of the system. When the X-ray focal spot was ideal (point source), the spatial resolution system fitted exactly the detector resolution, and it was a linear function of the system magnification (equation 2). Therefore, higher system magnification led to higher spatial resolution of the system when the X-ray focal spot is ideally small.

Figure 3 depicts the situation of the VRX CT scanner when the opening half angle is 21.9°. The position of cell#1 and cell#256 (the first and last active cell in each VRX detector arm) are designated by straight lines in magnification axis. Cell#1 and Cell#256 have 0.22 difference in magnification and it leads to 0.5 cycle/mm non uniformity of spatial resolution at this opening half angle. At this opening half angle, the detector resolution is lower than foal spot resolution. Therefore, the cells with higher magnification have higher spatial resolution. Because the focal spot resolution is much higher than detector resolution at this opening half angle, even focal spot size of 0.8 mm has no effect on spatial resolution of the system (figure 4). Since the spatial resolution of the system is limited by detector resolution, decreasing the opening half angle will decrease the apparent detector cells width (W in equation 1) and consequently the spatial resolution of the system will increase.

By reducing the opening half angle, the limiting effect of focal spot size appeared. At opening half angle of 10.6°, the spatial resolution of half of the detector cells (with higher magnification) were limited by the effect of foal spot size (figure 5). With ideal focal spot size at this opening half angle, the spatial resolution of the cell#256 would remain unchanged at 6 cycle/mm, but spatial resolution of the cell#1 would have increased from 5.7 to 7 cycle/mm.

At small opening half angles, the focal spot size limits the spatial resolution of the system to a gret extent (figure 6). At the opening half angle of 2.63°, the focal spot resolution was much lower than the detector resolution. So, the focal spot size is the dominant factor which determined the spatial resolution of the system at small incident angle. The spatial resolution for cell#1 is 5.7 cycle/mm and for cell #256 is 11.16 cycle/mm. As it is clear, the effect of foal spot size causes great spatial resolution non-uniformity. The focal spot size of 0.1 mm is ideally small for this VRX CT scanner and can eliminates the limiting effect of the focal spot size (figure 7). By focal spot size of 0.1 mm, the resolution of the system increased to more than 25 cycle/mm, and the non-uniformity of the spatial resolution

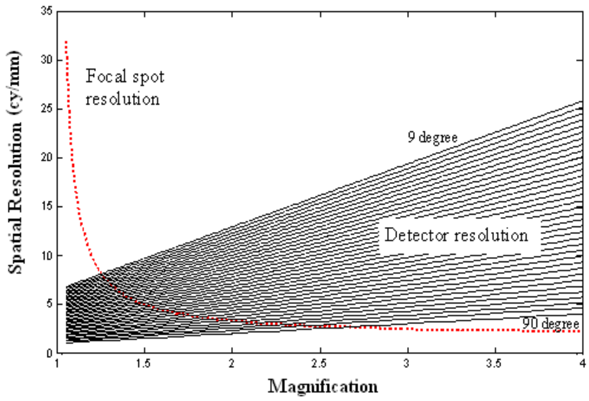

Figure 2. The trend of focal spot and detector resolution for opening half angles of 9° to 90° degree.

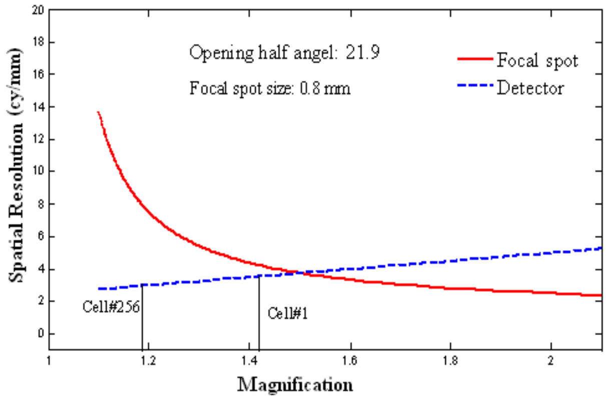

Figure 4. Spatial resolution of the VRX CT scanner at opening half angle of 21.9° with focal spot size of 0.8 mm.

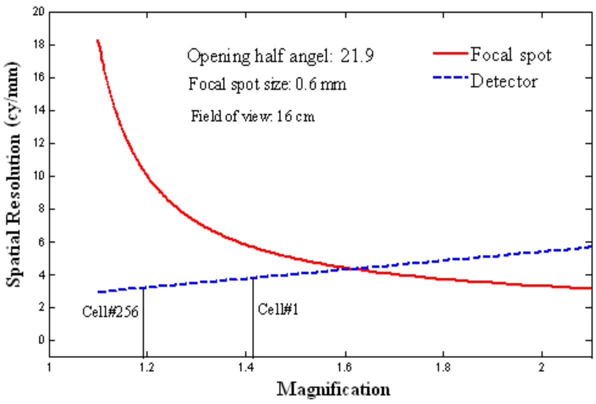

Figure 3. Spatial resolution of the VRX CT scanner at opening half angle of 21.9°.

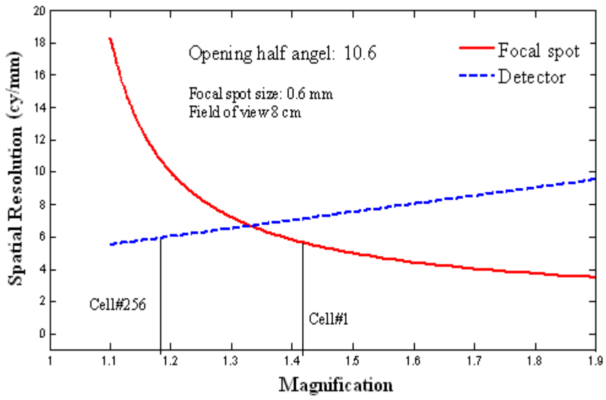

Figure 5. Spatial resolution of the VRX CT scanner for opening half angle of 10.6°.

along the detector length was less significant.

Figure 8 summarizes the effect of focal spot size of 0.6 mm on the spatial resolution of the VRX CT scanner. Since the cell#256 had lower magnification, the limiting effect of focal spot size appeared at smaller opening half angle for this cell. The effect of focal spot size and non-uniformity of the magnification caused a great spatial resolution deference between cell#1 and cell#256 at opening half angles of below 14°. Focal spot size of 0.1 mm minimized the spatial resolution non-uniformity and increased the spatial resolution of the system significantly (figure 9).

DISCUSSION

In variable resolution X-ray CT scanner, variable resolution is achieved by angulation of the detector arms. The angulation of the detector results in two specific features for VRX CT scanner. First, the optimum magnification varies at each opening half angle. Second, the magnification non-uniformity increases by reducing the opening half angle. Optimization of magnification at each opening half angle improves significantly the spatial resolution of the system. However, remaining on optimum magnification requires changing the object position at each opening half angle that has its own disadvantages [16].

Focal spot sizes of smaller than 0.6 mm has no significant improvement on spatial resolution of the system for opening half angles of above the 14°. The main factor that determines the spatial resolution of the system at opening half angles of 90° to 14° is detector resolution. So reducing the foal spot size has no effect. The effect magnifica-

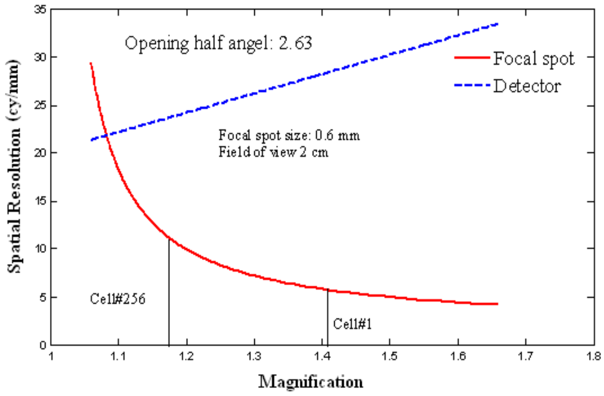

Figure 6. The situation of the VRX CT scanner at the opening half angle of 2.63°. The focal spot size greatly limits the spatial resolution of the system at this angle.

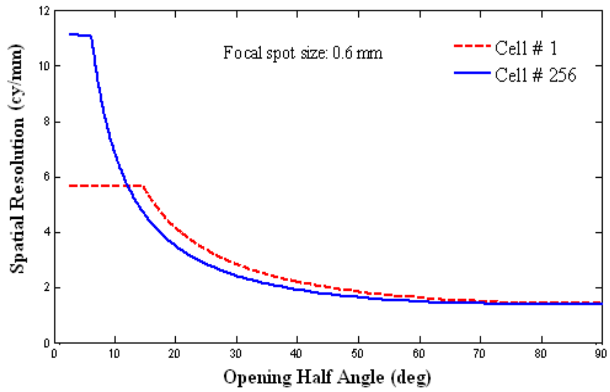

Figure 8. Spatial resolution of the VRX CT scanner at various opening half angles with focal spot size of 0.6 mm.

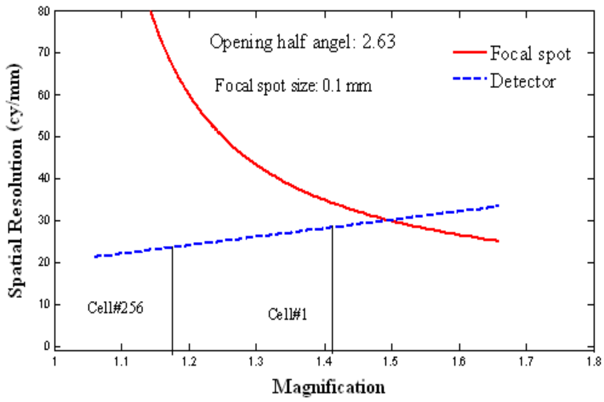

Figure 7. Spatial resolution of the VRX CT scanner at opening half angle of 2.63° with focal spot size of 0.1 mm.

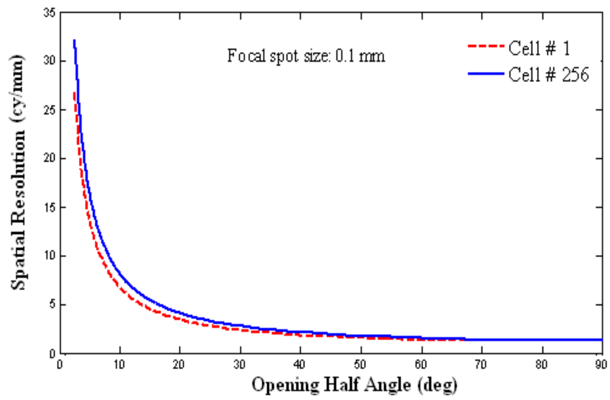

Figure 5. Spatial resolution of the VRX CT scanner for opening half angle of 10.6°.

tion non-uniformity is not severe at these opening half angles. The effect of focal spot size appears at opening half angles of below 14° and has two disadvantages. 1. The spatial resolution of the system remains constant at 5.7 cycle/mm for cell#1 and at 11.2 cycle/mm for cell#256. At these opening half angles, the spatial resolution of the system is no longer a function of opening half angle. 2. The focal spot causes great non-uniformity of spatial resolution along the detector length.

The limiting effect of focal spot size at small opening half angles is the main problem in practical measurement. In this case, the spatial resolution of the system is so deteriorated by focal spot size that, the practical measurement of detector resolution is so hard [(6)].

Focal spot size of 0.1 mm acts as an ideal point source for this VRX CT scanner. The spatial resolution rose up to 30 cycle/mm. furthermore, the spatial resolution changed as a function of the opening half angle at the entire range. By focal spot size of 0.1 mm, the detector resolution becomes lower than focal spot resolution at all opening half angles. Therefore, the effect of magnification non-uniformity is limited to the detector resolution (equation 1) and consequently the non-uniformity of spatial resolution decreased greatly.

Practically, foal spot size of 0.1 mm has some limitations. In VRX CT scanner, depending on the maximum necessary spatial resolution, the focal spot size can be chosen to satisfy the need.

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