An experimental study on the shift-variant MTF of CT systems using a simple cylindrical phantom

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ABSTRACT

The modulation transfer function (MTF) is a typical parameter to measure the spatial resolution, which is an essential factor for evaluating the performance of computed tomography (CT) systems. It is known that the CT system does not follow the shift-invariant manner because of the cone-beam geometry and the transformation from the cylindrical coordinates to the axial coordinates when the image reconstruction is employed. Several studies reported that if the position of impulse receded from the center of a region of interest (ROI), the MTF degraded continuously. In this study, the trend of shift-variant characteristics of CT systems was measured and analyzed using a novel multi-cylindrical phantom. This study used to determine a point spread function (PSF) and MTF of a CT system using a simple cylindrical phantom. First of all, the optimal diameter of cylinder phantoms was experimentally determined as 70 mm to obtain reliable PSFs. Two kinds of field of views (FOVs), 40 cm and 60 cm, were used to vary reconstructed pixel sizes. The shift-variant MTF curves were acquired at five off-center positions per FOV. For the effective analysis of MTF shift-variant, the integrated MTF values were calculated and used. In the result, the MTF slightly decreased as diameter increased from CT center in the central region within the distance of 10 cm. Moreover, a considerable MTF decrease suddenly occurred around the distance of 15 cm in the actual FOVs. The decreasing trend of the off-center spatial resolution of CT cannot be neglected in recent radiologic and radio-therapeutic fields requiring high degree of image precision, especially in sub-mm images. It is recommended that the ROI is laid on the CT center as close as possible. A novel cylindrical phantom was finally suggested to effectively measure PSFs with optimal diameters for clinical FOVs in this study. This phantom is cheap and convenient to use because it was only made of acrylic with simple geometry. It is expected that the spatial resolution of CT can be easily monitored using our methodology in clinical CT sites.

Keywords: Shift-variant, MTF, CT, PSF, acrylic cylindrical phantom

1. INTRODUCTION

The spatial resolution of a computed tomography (CT) is an essential factor for evaluating the performance of CT systems. One of metrics representing the spatial resolution of imaging systems is an impulse response function, whose Fourier pair is known as the modulation transfer function (MTF). The MTF means not only the system resolution, but the contrast transfer as a function of spatial frequency. Thus, the measurement of MTF characterizes the overall performance of signal transfer in the CT system. The MTF measurement of CT systems usually requires the measurement of point spread function (PSF), and thin wires, small sized metallic balls or metal plates with circular voids are used as impulse stimuli.\textsuperscript{1,2} However, it is hard to measure circularly distributed and finely sampled PSFs using aforementioned phantoms due to the difficulty in manufacture of thin cylindrical wires using the drawing process (< 0.1 mm diameter) and the geometrical misalignments of the small objects. Moreover, the phantoms made from high-Z materials, such as tungsten or gold, can give rise to the metal artifacts, which appear as streaks and shadows, in tomographs.

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In recent researches, it is reported that the object should be considered when overall performance of system are characterizing. And conventional high-Z metallic insert based impulse inputs cannot describe the signal transfer of system. Richard et al. suggested the task-based MTF using the cylindrical phantoms which were composed of soft tissue equivalent materials. The method used the circular edge technique to generate the edge spread function (ESF) across various contrast and noise levels. It provided a robust method for characterizing the spatial resolution. Ohkubo et al. devised an effective method for obtaining the line spread function (LSF) and PSF of CT system, and they validated the accuracy of the LSF and PSF of a CT system by comparing the simulated images with the images obtained from phantoms corresponding to the object function. However, the effect of the diameter of cylinder was not evaluated by the cylinder-based approach.4

There is an important concern in the measurement of MTFs of CT systems. It is known that the CT system violates the shift-invariant property because of the cone-beam geometry and the transformation from the polar coordinates to the Cartesian coordinates when the image reconstruction is employed. Therefore, the measured MTFs are dependent upon the positions where the PSFs are measured in the field of view (FOV) of CT systems. Kwan et al. reported that if the position of impulse becomes distant from the center of FOV, the MTF degrades continuously.1 To our knowledge, there has been no previous works characterizing the trend of shift-variant properties of MTFs in CT systems.

In these regards, we first designed a novel multi-cylindrical phantom consisting of 10 cylinders with different diameters ranging from 3 mm to 100 mm to quantify the effect of diameters. And then we measured cylindrical PSFs with various diameters considering the transfer functions of cylinders themselves to secure the independence of diameters of

![Fig. 1. The novel acrylic multi-cylindrical phantom with 10 diameters from 3 mm to 100 mm for PSF measurements](image)

![Fig. 2. (a) An example of CT image obtained by scanning the phantom with a diameter of 70 mm and (b) simulated object function with dA and dB](image)
phantoms. Finally, we characterized the trend of shift-variant MTFs due to the positions in the region of interests. This study aims to show the shift-variant property of CT systems and suggest a guideline of the performance evaluation procedures in the Fourier domain.

2. MATERIALS AND METHODS

2.1 Theory
For the MTF assessment of CT, it is essential to acquire a PSF or a LSF. In this study, the method proposed by Ohkubo, et al. was used to determine the PSF of CT systems. This method demonstrated that the PSF could be accurately measured. A cylindrical phantom whose shape and the CT number in the transverse plane do not vary at any position in the z direction perpendicular to the transverse plane is used. The scanned CT image \( I(x,y) \) of the phantom object \( O(x,y) \) can be acquired in a scan plane. A relationship between two functions can be given by

\[
I(x,y) = O(x,y) \ast \text{PSF}(x,y), \quad (1)
\]

Where \( \ast \) represents the two-dimensional (2D) convolution. Noise and artifact components are neglected. Using the Fourier transform, equation (1) can be transformed and rewritten as

\[
\text{PSF}(x,y) = F^{-1}\{ F[I(x,y)] / F[O(x,y)] \}, \quad (2)
\]

where the \( F \) and \( F^{-1} \) denote the 2D Fourier transform and the 2D inverse Fourier transform, respectively. Therefore, the PSF can be calculated according to equation (2).

2.2 Imaging parameters and phantom
The CT system which was assessed in this study was the GE LightSpeed 16 RT (GE Healthcare, Milwaukee, WI) for the CT simulation of radiation treatment planning. The phantom was scanned using 120 kVp, 330 mA, 2.5 mm slice thickness in axial mode. Two kinds of FOVs, 40 cm and 60 cm, were used to vary the reconstructed pixel size. For the measurement of MTF at off-center positions, the distances from the CT center to the phantom center were 0, 3, 6, 9, 12 cm in the FOV of 40cm, and 0, 5, 10, 15, 20 cm in the FOV of 60cm.

For the MTF assessment, a simple acrylic phantom with several cylinders was manufactured as shown in figure 1. We chose ten cylindrical objects with diameters of 3, 5, 7, 10, 20, 30, 40, 50, 70, and 100 mm. The cylinders were placed so that centers of them were laid on the same z axis. The thickness of each cylinder was 10 mm.

2.3 Determination of PSF, LSF, and MTF
The object function, \( O(x,y) \), was numerically simulated using the scanned image \( I(x,y) \). First, two regions of interest (ROI) were chosen as shown in figure 2(a). ROI\(_A\) was a square, whose side was equivalent to the radius of object cylinder in length. The center position of ROI\(_A\) was matched to the center position of cylinder in \( I(x,y) \). The ROI\(_B\) was a rectangular, which was located at the surroundings. The mean values in CT numbers in ROI\(_A\) and ROI\(_B\) were \( d_A \) and \( d_B \), respectively. The center position of the cylinder in \( I(x,y) \) was determined by calculating the center-of-mass of a binary image.

The size of \( O(x,y) \) was equivalent to that of \( I(x,y) \). The \( d_A \) value was assigned to the cylinder area, and \( d_B \) value was assigned to the surroundings as shown in figure 2(b). The PSF function was calculated by equation (2), and an example of PSF is shown in figure 3(a).

LSFs and MTFs were obtained from PSFs as expressed in equation (3) and (4), where \( f \) was the spatial frequency:

\[
\text{LSF}(x) = \int PSF(x,y) dy, \quad (3)
\]
However, the insufficient spatial resolution was inevitable because of the off-axis scanning for shift-variant MTF assessment. So, the PSF data were binned into 0.18-pixel-size bins in the slanted 45° direction as shown in figure 3(b).

Fig. 3. An example of 2D PSF images from the scanned images \( I(x,y) \) de-convolved by the object functions \( O(x,y) \)

Fig. 4. The schematic diagram of PSF\((x,y)\) projections in a slanted direction for the acquisition of LSF\((x)\). In this manner, data were binned into 0.18 pixel size (p) bins.

### 2.4 Measurement of off-center spatial resolution of CT

For the assessment of shift-variant MTFs, the cylinder phantom was iteratively scanned at off-center positions in CT. In the FOV of 40cm, five distances from center were used as 0, 3, 6, 9, 12 cm. In the case of 60 cm FOV, five distances from center were also used as 0, 5, 10, 15, 20 cm. The center of cylinder was carefully matched with the CT center and moved to given positions using laser positioning system before scanning.
3. RESULTS AND DISCUSSION

3.1 Optimal diameter of cylinder

Figure 5 shows the relationship between the diameters of cylinders and MTFs for the FOVs of 40 cm and 60 cm. The integrated MTF values from 0 to 1 line pairs/mm (lp/mm) were used for the effective comparison. In both curves, the integrated MTF value seems to converge on some values as the diameter of cylinder increases. For the quantitative analysis, the relative deviation of integrated MTF values, $\Delta iMTF(d)$, were calculated as follows:

$$\Delta iMTF(d) = \left| \frac{\int MTF_d(f) df - \int MTF_d(f') df'}{\int MTF_d(f) df} \right|,$$

where $d$ and $d'$ denote a diameter of cylinder and the next larger diameter, respectively, and $f$ means the spatial frequency in lp/mm. The $\Delta iMTF(d)$ values with the FOV of 40 cm are presented in figure 6(a). In the diameters of 7–30 mm, the deviations were 4.1–5.4 %, and a steep decline of deviations were observed in the diameter of 40 mm. The mean deviation at the last three diameters was only 0.76%. In the case of 60 cm FOV, the deviations were at the range of 18.4–46.4% with the diameters of 10–40 mm. But the mean deviation at the last two diameters was 2.3% as shown in figure 6(b). Therefore, the cylinder phantoms of which diameters are larger than 40 mm and 50 mm are required to measure reliable PSFs in the FOV of 40 cm and 60 cm, respectively. The fluctuation of the calculated $\Delta iMTF(d)$ in the FOV of 60 cm seemed to be larger than that in the FOV of 40 cm. It may be caused by different pixel sizes between FOVs. The smaller pixel size enables the more accurate image sampling, and vice versa.

The PSF is ideally independent of the diameter of cylinder phantom, because the PSF is an inherent characteristic of an imaging modality. But, the diameter of cylinder actually affects the PSF performance because of the limited pixel sizes of reconstructed CT images. The pixel sizes of scanned CT images and the recommended diameters of cylinders are presented in table 1.

<table>
<thead>
<tr>
<th>FOV (cm)</th>
<th>Reconstructed pixel size (mm)</th>
<th>Recommended diameter of cylinder (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>0.781</td>
<td>&gt; 40</td>
</tr>
<tr>
<td>60</td>
<td>1.172</td>
<td>&gt; 50</td>
</tr>
</tbody>
</table>

3.2 Off-center spatial resolution of CT

We used the cylinder phantom with the diameter of 70 mm to measure the off-center PSFs in both FOVs referring to table 1. The MTF values gradually decreased as the distance from CT center increased in the FOV of 40 cm as shown in figure 7(a). In the case of 60 cm FOV, the MTF values also decreased with the exception of a steep decline between the distances of 10 and 15 cm in figure 7(b).

The behavior of spatial resolution of CT system at the off-center positions are clearly presented in figure 8. The MTF values seemed to gradually decrease as the distance from CT center increased in central region within the distance of 10 cm. This phenomenon essentially arises during the reconstruction process from the polar coordinates to the Cartesian coordinates. Meanwhile, the considerable MTF decrease suddenly occurred around the distance of 15 cm. It may be caused by a reconstruction kernel, which is usually applied to enhance the overall image quality. The standard kernel was only used in this study.
The decreasing trend of the off-center spatial resolution of CT cannot be neglected in recent radiologic fields requiring the high degree of image precision, especially in sub-mm images. The CT image with high precision is also essential in the state-of-the-art radiation treatments, e.g. intensity-modulated radiotherapy and stereotactic body radiotherapy. In these cases, moreover, CT images are used not only to diagnose but also to do treatment planning. So, it is recommended that the ROI is laid on CT center as close as possible. Additionally, the properties of the used reconstruction kernels should be considered, especially, in outer regions.

4. CONCLUSIONS

We evaluated the trend of shift-variant MTFs with a normal CT scan condition and the standard kernel. The gradual decrease of CT spatial resolution, especially a steep decrease in outer regions, should be considered in recent radiologic and radio-therapeutic fields. A novel cylindrical phantom was suggested to effectively measure PSFs with optimal diameters for clinical FOVs. Our phantom is cost effective and convenient to use because it was only made of acryl with simple geometry. It is expected that the spatial resolution of CT can be easily monitored using our methodology in clinical CT sites.
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