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Modulation transfer functions of computed tomography using a cylindrical uniform phantom

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1. Introduction

Evaluating the image quality obtained from a computed tomography (CT) system using objective methods is crucial. The quality of CT images is determined by several factors, including contrast, spatial resolution, noise, and artifacts, among which spatial resolution significantly impacts overall image quality [1,2].

Spatial resolution refers to the ability to distinguish between small differences in the features represented in the image. A quantitative measure that can evaluate this spatial resolution is the modulation-transfer function (MTF) [2]. The MTF is a function that expresses the relative contrast of an output signal compared to the input at each spatial frequency, which corresponds to the inverse of the spacing between contrast objects per unit length [3].

The MTF is the Fourier pair of the point-spread function (PSF). More precisely, the Fourier pair of the PSF is the optical transfer function (OTF), and the magnitude of the OTF (ignoring phase) is the MTF. However, obtaining the PSF, which is the system's response to a delta function, is extremely difficult. Instead, it is common practice to derive the 1D MTF by obtaining the line-spread function (LSF) in a specific direction. To obtain the LSF, a very narrow slit is required, but this approach is impractical. Typically, the LSF is derived by measuring the edge-response function (ERF), which is relatively easier to measure, and then differentiating it. However, the method used to calculate the MTF can vary depending on which phantom is utilized as the impulse signal to determine the system's response function.

In this study, following the ASTM E1695 [4], we calculate the MTF using a cylinder phantom. Additionally, we investigate the impact of various factors on the measurement and calculation of MTF, including X-ray beam hardening, the size of the region of interest (ROI) for ERF extraction, and noise reduction methods. The MTF will be analyzed and discussed in relation to these factors.

2. Methods and Materials

2.1 MTF calculation

For the CT simulation, an aluminum cylinder with a radius of 15 mm and a height of 50 mm was modeled, and simulations were performed using the RT simulation module of the commercial non-destructive testing simulation tool, CIVA (Version 10.0b, Extende, France). The MTF calculation procedure described in ASTM E1695 can be summarized as follows:

① A circle with a radius corresponding to the edge of the disk (r_c) is determined, and circles are set inside and outside the edge, with the space between them designated as the ROI.

② The distance r from the center of the disk to all voxels within the ROI is calculated. After setting bin intervals, the voxel values within each bin are averaged and arranged in ascending order of r

③ To smooth the arranged data, bins for smoothing are set, and a cubic spline regression is performed to generate a cubic polynomial. The central value of each bin is then replaced with the central value of the cubic polynomial to achieve smoothing.

④ The LSF is obtained by differentiating the cubic polynomial derived earlier.

⑤ The MTF is obtained by applying the fast Fourier transform (FFT) to the LSF and performing zero-frequency normalization.

2.2 Factors that cause MTF distortion

The first factor contributing to MTF distortion is X-ray beam hardening. Beam hardening occurs due to the differential attenuation between high-energy and low-energy photons in a spectrum with various energies. This effect causes cupping artifacts, where voxel values at the edges of a cylinder are higher due to shorter X-ray paths, and those at the center are lower due to longer paths, even though the cylinder is composed of a uniform material. To investigate the impact of beam hardening, simulations were conducted using an unfiltered X-ray spectrum, a filtered X-ray spectrum, and a mono-energetic beam.

The second factor is the size of the ROI. The size of the ROI determines the extent of the tail regions at the start and end of the ERF and LSF. A rapid change to zero in the LSF at the end of the ROI can lead to artifacts due to spectral leakage. To study the effect of ROI size, MTF was calculated and compared for four different ROI sizes: 1.5 mm, 3 mm, 6 mm, and 12 mm.

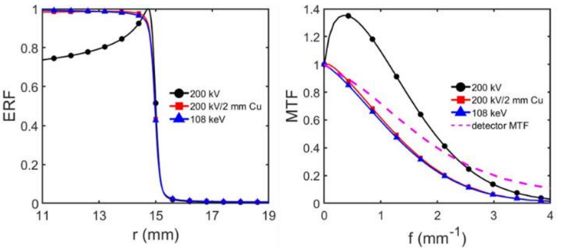

Fig. 1. Effects of beam hardening artifacts on ERF and MTF

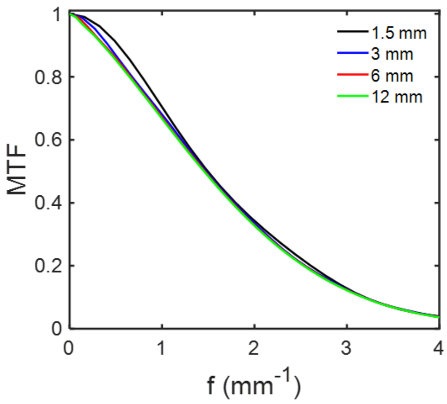

Fig. 2. The MTFs obtained from ROIs with different extents, where the ERFs were extracted

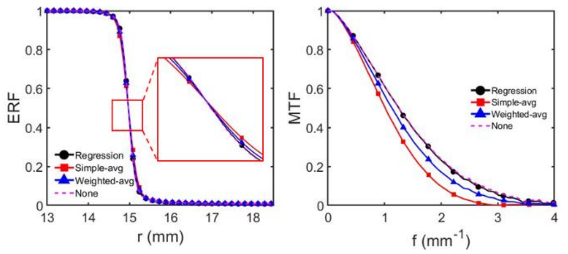

Fig. 3. Effects of noise reduction algorithms on ERF and MTF

The third factor is the noise reduction method. ASTM E1695 suggests using cubic spline regression analysis. To assess its performance, this method was compared with simple averaging and Gaussian weighted averaging techniques.

3. Preliminary Results

Fig. 1 shows that the ERF graph demonstrates significant beam hardening for the unfiltered spectrum, resulting in an overestimation of the MTF.

Fig. 2 reveals that the MTF exhibits oscillations when the ROI is very small, specifically 1.5 mm, likely due to spectral leakage caused by data truncation.

As shown in Fig. 3, the ERF graph indicates that the slope is steepest for cubic spline, followed by Gaussian weighted averaging and simple averaging. This order reflects how effectively each method captures the edge of the disc, with the MTF results corresponding to the steepness of the ERF slope.

4. Conclusion

The effects of various factors on MTF measurement were investigated through simulations. Beam hardening was found to significantly overestimate the MTF, making correction essential. When the ROI for extracting the ERF is very small, MTF oscillations can occur, suggesting that a larger ROI should be used if possible. Finally, in terms of noise reduction, the cubic spline regression analysis recommended by ASTM was confirmed to be an appropriate method.

Since this study was conducted using computer simulations, future research will focus on validating the MTF measurement process using experimental data that considers CT system factors, such as X-ray focal spot size and detector resolution, as well as various noise sources.

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