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Object shape dependency of in-plane resolution for iterative reconstruction of computed tomography

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Abstract

The present study aimed to investigate whether the in-plane resolution property of iterative reconstruction (IR) of computed tomography (CT) data is object shape-dependent by testing columnar shapes with diameters of 3, 7, and 10 cm (circular edge method) and a cubic shape with 5-cm side lengths (linear edge method). For each shape, objects were constructed of acrylic (contrast in Hounsfield units [ΔHU] = 120) as well as a soft tissue equivalent material (ΔHU = 50). For each shape, we measured the modulation transfer functions (MTFs) of IR and filtered back projection (FBP) using two multi-slice CT scanners at scan doses of 5 and 10 mGy. In addition, we evaluated a thin metal wire using the conventional method at 10 mGy. For FBP images, the MTF results of the tested objects and the wire method showed substantial agreement, thus demonstrating the validity of our analysis technique. For IR images, the MTF results of different shapes were nearly identical for each object contrast and dose combination, and we did not observe shape-dependent effects of the resolution properties of either tested IR. We conclude that both the circular edge method and linear edge method are equally useful for evaluating the resolution properties of IRs.

Keywords

computed tomography, iterative reconstruction, modulation transfer function, spatial resolution

Introduction

Currently, filtered back projection (FBP) is considered the standard computed tomography (CT) image reconstruction method and features the spatial resolution properties that are mostly independent of image noise and object contrast because of the linear process of this method. As a result, almost all clinical CT systems use FBP for image output. Recently, iterative reconstruction (IR) techniques have been introduced into clinical use; however, the non-linear properties of these techniques have led to reports of spatial resolution variability depending on image noise levels and object contrast [1-5]. Accordingly, a task-based technique that measures modulation transfer functions (MTFs) from the circular edges of disk (columnar) objects with different CT value contrasts (i.e., circular edge method) was suggested for evaluating the spatial resolution of IR images; in addition, the non-linear spatial resolution properties of IRs have been evaluated using this method [3,4]. In the original paper on the task-based MTF (MTF_{Task}) concept [4], a well-known phantom—ACR CT phantom—for CT quality assurance was used, and one of the several sections in the phantom, which includes disk objects with −95, 120, and 955 Hounsfield units (HU) at 120 kV for CT value accuracy, was acquired with a wide range of radiation doses. MTF_{Tasks} were measured from circular edges of the three disk objects and it was demonstrated that MTF_{Tasks} of both two IR techniques varied depending on contrast and dose.

Although the circular edge method has been used effectively for IR, the effect of the disk diameter on the MTF_{Task} of IR has not been investigated. Notably, another candidate for MTF_{Task} measurements has been devised; this edge method uses angled linear edge images [1, 6, 7] obtained by scanning an object with flat surfaces (e.g., cube or rectangular solid) and appears to be applicable to MTF_{Task} because the object contrast can be adjusted via object material selection. However, the edge method has not been used to evaluate the MTF_{Task} of IR, and the MTF_{Task} of IR obtained with the circular edge method and linear edge method has not been compared. In particular, shape dependency of IR resolution would complicate task-based evaluations because the object shape would require inclusion as a task. The present study aimed to examine the shape dependency of the MTF_{Task} of IRs using columnar objects with different diameters as well as cubic objects.

Materials and Methods

CT scanner and iterative reconstruction

We employed two multi-detector row CT scanners: a SOMATOM Definition Flash (DF; Siemens Healthcare, Erlangen, Germany) and Discovery CT750 HD (GE Healthcare, Milwaukee, WI, USA) equipped with Sinogram Affirmed Iterative Reconstruction (SAFIRE) and Adaptive Statistical Iterative Reconstruction (ASIR), respectively. SAFIRE, which features strength levels of 1–5 with 5 = best noise reduction, is used to eliminate artifacts at the projection data level and facilitates high-speed reconstruction by performing noise reduction and edge-preserving via iteration in the image domain [8]. ASIR reduces both noise and artifacts at the raw data level during iteration in both forward and back projection [8] and can blend IR images with FBP from 0 to 100% at 10% intervals; 100% ASIR yields the greatest noise reduction.

Tested objects

An overview of the phantoms used in this study is shown in Figure 1. An acrylic cylindrical case with a diameter of 200 mm was used to enclose tested objects with different shapes. Specifically, the objects were either columnar with diameters of 3, 7, or 10 cm and a height of 10 cm, or cubic with an edge length of 5 cm. For each shape, two objects were generated from a tissue equivalent material

(SZ-207, Kyoto Kagaku, Kyoto, Japan) and acrylic. Using these objects, we were able to examine the resolution properties for different curvatures of the circular edge, as well as differences between the circular edges of columnar objects and the linear edges of cubic objects. The CT numbers of the tissue equivalent material (SZ-207) and acrylic at 120 kV were approximately 50 Hounsfield units (HU) and 120 HU, respectively. Each object was placed co-axially in the cylindrical case, which was then filled with water.

A wire phantom, comprising a 0.15-mm copper wire enclosed in a 50-mm-diameter cylindrical acrylic case filled with water, was used for the conventional MTF measurement method. For FBP images, the MTF results obtained with the wire method were compared with those determined using columnar and cubic objects for validation of the measurement and calculation techniques used herein.

The circular edges of the 3-, 7-, and 10-cm columns were located at different distances from the rotation axis. However, our centric positioning yielded very similar geometry blurring conditions for all diameters because the distances between the x-ray focal spot and each on the circular edge along a ray from the focal spot did not significantly differ among the three diameters. Therefore, the three diameters exhibited near-equal geometric blurring at points of tangency and thereby could be used for shape (curvature) dependency evaluations. If the columnar objects are not centrally placed, the similarity of the geometry blurring is disrupted; accordingly, shape dependency could not be evaluated using columnar objects with different diameters.

Data acquisition

For a columnar object, the central axis was set parallel to the rotation axis of the CT system with a 10-mm offset position in the y-direction. This offset positioning was adopted to avoid a specific MTF_{Task} result (abnormally lower MTF_{Task}) when the central axis was accurately matched to the rotation axis of the CT system, a phenomenon that was observed in our preliminary experiments. The central axis of the cubic object was matched to the rotation axis of the CT system such that the measured surface (one of the vertical surfaces) was located at a 25-mm offset position. In addition, the cubic object was angled slightly (approximately 2.5º) with respect to the x–y coordinate in order to obtain the over-sampled edge profile commonly used with the edge method [7].

The detector configurations were 0.6 ∗ 128 mm and 0.625 ∗ 64 mm for the SOMATOM DF and CT750 HD, respectively. The scan conditions included a tube voltage of 120 kVp, tube rotation time of 0.5 s, and pitch factors of 0.6 (SOMATOM DF) and 0.516 (CT750 HD). CT images were reconstructed using a 200-mm display field of view (DFOV), nominal slice thicknesses of 0.75-mm (SOMATOM DF) and 0.625-mm (CT750 HD), and reconstruction kernels for FBP of B40 (SOMATOM DF) and Standard (CT750 HD). The reconstruction kernels for IRs were I40 at a strength of 5 (SOMATOM DF) and ASIR at a 100% blending rate (CT750 HD). The estimated acquisition doses in the volume CT dose index ($CTDI_{vol}$) were 5 and 10 mGy for IR. For the FBP images, only 10 mGy was used, as well as objects only with acrylic, because the resolution property of FBP is independent of dose and object contrast. [1–4].

For each object, 100–600 images were obtained to utilize the image averaging technique for improving the MTF_{Task} measurement accuracy, as described in the next section. Accordingly, we carefully placed the phantom so that the central axes of the columnar and cubic objects were accurately parallel to the rotation axes of the CT systems, and then repeated the acquisition to obtain a sufficient number of images. In total, 100 and 50 images per acquisition could be obtained for the columnar and cubic objects, respectively, and 300 images, for example, were required for objects with SZ-207 at 10 mGy so as to obtain the sufficient MTF_{Task} accuracy. The wire phantom was also placed so that its axis was parallel to the rotation axis and scanned at a dose of 10 mGy. Wire CT images were reconstructed using the same conditions used for columnar and cubic objects, except for

DFOV which was set at 50 mm to detect the accurate point spread function obtained from the wire image.

Phantom image data analysis

The image sets of each columnar and cubic object were averaged into single images prior to the MTF_{Task} data analysis. This yielded a sufficiently high contrast-to-noise ratio (CNR) of the averaged image (≥25), according to a report in which the image averaging technique was used to improve the evaluation accuracy of the IR resolution property of a bar pattern phantom [9]. Our preliminary experiments involving this high CNR condition indicated that the standard deviation for five measurements fell within 0.007 for frequency ranges <10% MTF_{Task}.

For columnar objects, a one-dimensional (1D) edge spread function (ESF) from a disk image (axial image of the columnar object) was obtained using the circular edge technique reported by Richard et al. [4]. The bin width in the binning process used to create equidistant ESF data and simultaneously reduce noise was set to one fifth of the pixel pitch—0.39 mm—corresponding to a DFOV of 200 mm, as mentioned earlier. For cubic objects, a linear edge from a vertical object surface was analyzed, and the various pixel values around the slanted linear edge were projected onto a line orthogonal to the edge line to obtain a 1D synthetic ESF. The bin width was also set to one fifth of the pixel pitch. For wire images, a 256 x 256 pixel sub-image around the wire was analyzed using a 2D fast Fourier transformation; subsequently, the 2D MTF was averaged radially to generate the final 1D MTF profile.

Validation of MTF measurement and calculation techniques

For the FBP images that have the linear property, MTF_{Task} are measured from the columnar and cubic objects must agree with the MTF measured from the wire phantom, irrespective of the dose and the object contrasts [4]. Thus, we validated our measurement and calculation techniques by comparing MTF_{Task} of the acrylic objects with MTF of the wire phantom. Only the acrylic objects with 10 mGy were used for MTF_{Task} due to the FBP resolution property independent of dose and contrast.

Shape dependency analysis

MTF_{Task} results measured using the 3-, 5-, and 7-cm columnar and cubic objects were compared to examine the shape dependency of two IRs, respectively, for the materials of acrylic and SZ-207; dose levels were 5 and 10 mGy.

Dose and contrast dependency analysis

Although the dose and contrast dependencies of IRs have demonstrated in the recent papers [1-4], we performed data comparisons to confirm the dependencies for conditions used in this study. For the data analysis, MTF_{Task} results of the two dose levels (5 and 10 mGy) and the MTF_{Task} results of FBP were compared, respectively, for acrylic (120 HU) and SZ-207 (50 HU).

Results

The reproducibility of our MTF measurements was sufficiently high as a result of an image-averaging technique that yielded high CNRs (>25); accordingly, error bars are not indicated on the MTF results.

Validation of MTF measurement and calculation techniques

Figure 2 presents the comparison between MTF_{Task} (acrylic columnar and cubic objects) and MTF (wire) for FBP images. The MTF result of the wire and the MTF_{Task} results of the columnar and cubic objects were almost identical with each CT system and the difference in 50% MTF was <5.0%, thus demonstrating the validity of our analysis techniques of MTF_{Task} for the respective shapes.

Shape dependency

Figures 3 and 4 respectively present the MTF_{Task} results of SAFIRE and ASIR images of acrylic objects obtained at 5 and 10 mGy. These results were almost identical, regardless of object shape, at each radiation dose, with a difference in 50% MTF_{Task} between the shapes of ≤2.6%. A similar analysis of SZ-207 objects, presented in Figures 5 and 6, also failed to demonstrate shape dependency, with a difference in 50% MTF_{Task} of ≤2.9%.

Dose and contrast dependency

Figure 7 presents the MTF_{Task} results of IR images of the 3-cm acrylic columnar object at 5 mGy and 10 mGy and the MTF_{Task} result of FBP images. Although SAFIRE yielded a higher MTF_{Task} compared with FBP, increased by 44.2% for 5 mGy and 51.8% for 10 mGy at 0.5 cycles/mm, ASIR yielded a significantly lower MTF relative to FBP, decreased by 57.7% for 5mGy and 50.1% for 10 mGy at 0.5 cycles/mm. The resolution properties of the soft tissue material were not maintained with either SAFIRE or ASIR, as shown in Figure 8, and the MTF_{Task} values at 0.5 cycles/mm decreased by 18.4% (5 mGy) and increased by 7.9% (10 mGy) with SAFIRE, and decreased by 65.2% (5 mGy) and 64.3% (10 mGy) with ASIR.

Discussion

In this study, the spatial resolution properties of SAFIRE and ASIR did not exhibit shape dependency when used to evaluate columnar objects with different diameters and cubic objects. In other words, circular and linear edges were equally useful for evaluating the resolution properties of IRs; in addition, circular edge diameters of ≤10 cm did not affect MTF_{Task} evaluation. Thus it was demonstrated that shape consideration appears to be unnecessary with respect to the resolution properties of IRs.

We evaluated the MTF_{Task} for contrasts of 120 HU and 50 HU; notably, previous studies using MTF_{Task} of IR have not evaluated a contrast of 50 HU [4, 10–12]. In our results, significant differences were observed between 50 and 120 HU, especially with SAFIRE, and the spatial resolution was not maintained at a contrast of 50 HU. However, it is important to maintain resolution for contrasts of approximately 50 HU when evaluating detailed structures such as coronary arteries and deep venous thrombosis [13, 14]. Therefore, our results for the 50-HU contrast are noteworthy with regard to spatial resolution properties of IRs in various clinical situations. For ASIR, resolution was not maintained even at a contrast of 120 HU, although still further degradation was observed at 50 HU. From there results, it was demonstrated that the MTF_{Task} of IR was sensitive for the middle contrast level between 50 and 120 HU, depending on the IR technique, and that such a middle contrast level is necessary for evaluating the edge preservation ability of IRs.

For IR images, the spatial resolution of IR varies as a function of signal contrast and pixel noise due to the nonlinear behavior of image quality [10, 15]. This nonlinearity could be found in our results, even though object locations were limited to the phantom center. In terms of dose dependence, SAFIRE showed significant decreases in MTF_{Task} with a decrease in dose from 10 mGy to 5 mGy at the 50 HU contrast, whereas slight decreases were observed for both SAFIRE and ASIR at the 120 HU contrast. For the contrast dependence, both SAFIRE and ASIR showed decreases in

MTF_{Task} with a decrease in contrast from 120-HU to 50-HU, whereas SAFIRE indicated more significant dependence than did ASIR. Therefore, the nonlinear properties of IR techniques have also been demonstrated in our results.

The task-based method as used in this study can provide useful results such that specific properties which may be related to the different tasks of interest can be obtained. However, it would require a number of measurements corresponding to various tasks; thus, it would be difficult to cover the full spectrum of imaging tasks [15]. Results obtained from the task-based method may not be generalizable to all clinical protocols [16].

Although we tested both circular edges with different diameters and a linear edge shape in this study, these might not be sufficient for an investigation of shape dependency. However, it is difficult to use objects with irregular edges for MTF measurement because the creation of appropriate synthetic ESF forms is almost impossible. In addition, different curvatures and linear-like edges are often observed along the edges of human organs on axial CT images. Therefore, it appears that our tested object shapes were consistent with an evaluation of shape dependency corresponding to clinical situations. Although smaller columnar object diameters might be needed for a more accurate demonstration of shape dependency, it was difficult to obtain sufficient accurate MTF_{Tasks} because of the insufficient numbers of data sampling at such small diameters. However, IRs have been applied in coronary CT angiography to reduce its relatively high radiation dose [17–19], and thus, the edge preservation ability for coronary arteries with small diameters could be accurately evaluated as one of the clinical imaging tasks. Our results do not correspond to this task, and thus, further investigations are needed to improve the task-based MTF measurement method.

Conclusion

The tested IRs (SAFIRE and ASIR) did not reveal any shape dependency of the spatial resolution property at different doses (5 and 10 mGy) or contrast levels (120 and 50 HU). These results suggest that both the circular and linear edge methods are equally effective for resolution property evaluations of IRs and the diameters of circular edges do not require consideration.

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Fig. 1

Phantom overviews. (a) Columnar and (b) cubic objects were enclosed in a 200-mm-diameter acrylic cylindrical case filled with water. For each object shape, two objects made of acrylic or a soft tissue-equivalent material were prepared.

Fig. 2

MTF result of a wire phantom and MTF_{Task} results for acrylic objects with different shapes obtained using FBP with (a) SOMATOM DF and (b) CT750 HD at 10 mGy.

Fig. 3

MTF_{Task} results of SAFIRE images for acrylic objects obtained at (a) 10 and (b) 5 mGy.

Fig. 4

MTF_{Task} results of ASIR images for acrylic objects obtained at (a) 10 and (b) 5 mGy.

Fig. 5

MTF_{Task} results of SAFIRE images for objects made of a soft-tissue-equivalent material obtained at (a) 10 and (b) 5mGy.

Fig. 6

MTF_{Task} results of ASIR images for objects made of a soft-tissue-equivalent material obtained at (a) 10 and (b) 5mGy.

Fig. 7

MTF_{Task} results of IR images with different doses for acrylic object and of FBP images. (a) SAFIRE and (b) ASIR.

Fig. 8

MTF_{Task} results of IR images with different doses for objects made of a soft tissue-equivalent material and of FBP images. (a) SAFIRE and (b) ASIR.