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

Tadanori Takata [a,b,*], Katsuhiro Ichikawa [c], Wataru Mitsui [a], Hiroyuki Hayashi [a], Kaori Minehiro [a], Keita Sakuta [a], Haruka Nunome [a], Kousuke Matsubara [c], Hiroki Kawashima [c], Yukihiro Matsuura [a], Toshifumi Gabata [d]

[a] Department of Diagnostic Radiology, Kanazawa University Hospital, 13-1 Takara-machi, Kanazawa, Ishikawa 920-8641, Japan
[b] Graduate School of Medical Science, Kanazawa University, 5-11-80 Kodatsuno, Kanazawa, Ishikawa 920-0942, Japan
[c] Institute of Medical, Pharmaceutical and Health Sciences, Kanazawa University, 5-11-80 Kodatsuno, Kanazawa, Ishikawa 920-0942, Japan
[d] Department of Radiology, Graduate School of Medical Science, Kanazawa University, 13-1 Takara-machi, Kanazawa, Ishikawa 920-8641, Japan

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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.

1. 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

* Corresponding author at: Department of Diagnostic Radiology, Kanazawa University Hospital, 13-1 Takara-machi, Kanazawa, Ishikawa 920-8641, Japan.
E-mail address: t-takata@med.kanazawa-u.ac.jp (T. Takata).

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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.

2. Materials and methods

2.1. 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.

2.2. Tested objects

An overview of the phantoms used in this study is shown in Fig. 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.

2.3. 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 2.5°) 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

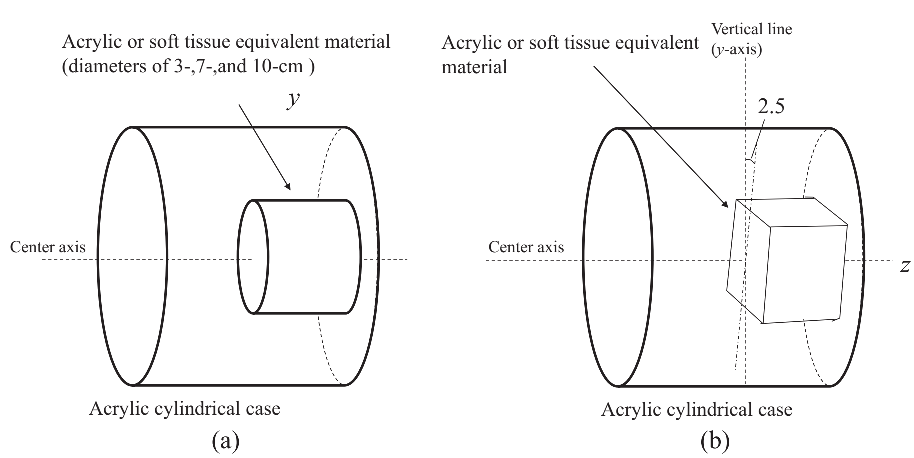

Figure 1. Phantom overviews. (a) Columnar and (b) cubic objects were enclosed in a 200-mm-diameter acrylic cylindrical case filled with water. For each object shape, two objects made of acrylic or a soft tissue-equivalent material were prepared.