Three-dimensional CT imaging in extensor tendons using deep learning reconstruction: Optimal dose and reconstruction parameters

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Research Article

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Abstract

The purpose of this study was to evaluate the optimal tube current and reconstruction parameters in extensor tendons 3-dimensional computed tomography (3D CT) using deep learning reconstruction, using iterative reconstruction as a reference. In phantom study, a cylindrical phantom with a 3 mm rod simulated an extensor tendon was used. The phantom images were scanned at tube current of 50, 100, 150, 200, and 250 mA. In the clinical study, nine hands in eight patients underwent CT of hand tendons. All images were reconstructed using advanced intelligent clear-IQ engine (AiCE) parameters (body, body sharp, brain CTA, and brain LCD) and adaptive iterative dose reduction three dimensional (AIDR 3D). Objective image quality for detectability of tendons was evaluated by calculated the low-contrast object specific contrast-to-noise ratio (CNR_{LO}) in our phantom study and CNR and coefficient of variation (CV) in the clinical study, respectively. In phantom study, CNR_{LO} (200 mA) of AiCE parameters (body, body sharp, brain CTA, and brain LCD) and AIDR 3D were 5.2, 5.3, 5.3, 5.8, and 5.0, respectively. In the clinical study, AiCE brain CTA was higher CNR and lower CV values than other reconstruction parameters. AiCE without dose reduction may be a useful strategy to further improve image quality of extensor tendons 3D CT. Our study suggests that the AiCE brain CTA is more suitable for extensor tendons 3D CT than other AiCE parameters.

Introduction

Extensor and flexor tendons can be injured in hand trauma, rheumatoid arthritis, and osteoarthritis, and are commonly examined using echography, magnetic resonance imaging (MRI), computed tomography (CT) [1–6]. Among these examinations, CT can identify the extensor and flexor tendons as a 3-dimensional (3D) image with volume rendering [4–6]. It has been reported that 3D CT is useful for confirming the clinical diagnosis of extensor and flexor tendons [5, 6]. Accurate 3D images that can determine the condition and location of tendons may preclude the need for surgery and assist with surgical planning. On the other hand, Sunagawa et al indicated that the usefulness of 3D CT imaging in the evaluation of extensor tendons is inferior in the evaluation of flexor tendons and some restrictions [6]. Certainly, creating 3D images of extensor tendons is often challenging because extensor tendons is thinner, closer to skin and bone, and has a smaller the CT value difference between structures such as tendons and muscles than the flexor tendons. Therefore, reducing image noise and improving contrast between tendons and muscles by making the CT value difference between tendons and muscles are important for 3D images of extensor tendons. The 3D CT scan of tendons is recommended to be set at high tube current to reduce image noise [7].

Recently, a deep learning-based reconstruction (DLR) technique using a deep convolutional neural network has been introduced. A commercially available DLR for CT of Canon, advanced intelligent clear-IQ engine (AiCE, Canon Medical Systems, Otawara, Japan), is trained to differentiate signal from noise and can suppress noise. Thus, AiCE reconstruction technique has improved image noise and enables a reduction of radiation dose maintaining image quality compared to CT images using conventional iterative reconstruction (IR). It has been reported that AiCE is useful in various regions such as chest,
cardiac, abdomen, CT angiography, and orthopedics [8–14]. However, it is not clear whether extensor tendons CT images reconstructed using AiCE enable a decrease in image noise and a reduction of radiation dose to better identify extensor tendons on 3D images. In addition, although the manufacturer-recommended AiCE parameter for soft tissue is AiCE body sharp, the optimal AiCE reconstruction parameter for 3D CT of extensor tendons is unclear. As a result, we investigated the optimal radiation dose using AiCE and the choice of AiCE reconstruction parameters in 3D CT of extensor tendons. The purpose of this study was to evaluate the optimal tube current and reconstruction parameters in extensor tendons 3D CT using AiCE, using IR as a reference.

Materials and methods

Phantom design

In this study, we used a cylindrical phantom with a 3 mm acrylic cylindrical rod to simulate an extensor tendon (Fig. 1). The diameter of the phantom was 50 mm. The phantom was filled with dilute contrast agent. The CT value difference between the cylindrical rod and the background was set to Δ20 Hounsfield units (HU) to correspond to the contrast between extensor tendons and muscle in CT of hand tendons.

Patient population

A total of eight patients were included in this study. All patients underwent CT of hand tendons from September 2021 to September 2022 at our hospital, Gifu, Japan. We evaluated CT images of nine hands in these patients (only right hands, three patients; only left hands, four patients; both hands, one patient). The gender was 50% men. The average value of age was 61 ± 9 years.

CT image acquisition

All CT images were performed using a 80-detector row CT scanner (Aquilion PRIME SP; Canon Medical Systems, Otawara, Japan). The CT acquisition parameters were as follows: acquisition mode, helical; gantry rotation time, 0.75 s/rotation; calibration field-of-view (FOV), 320 mm; tube voltage, 120 kV.

In the phantom study, CT images were performed with tube current of 50, 100, 150, 200, and 250 mA. The volume CT dose indexes (CTD1VOL) for each tube current were 2.6, 5.2, 7.8, 10.5, and 13.1 mGy. The number of scans was 50 times. Reconstruction conditions were slice thickness of 1.0 mm and display-FOV of 100 mm.

In the clinical study, CT images were performed with tube current adjusted by automatic exposure control with a reference noise index of 2.0-2.5. Reconstruction conditions were slice thickness of 1.0 mm and display-FOV of 100–130 mm.
All CT images were reconstructed with adaptive iterative dose reduction three dimensional (AIDR 3D, Canon Medical Systems, Otawara, Japan) and four different parameters of AiCE (body, body sharp, brain CTA, and brain LCD). Reconstruction kernel with AIDR 3D was FC05 (soft-tissue kernel).

**Data analysis**

**Phantom study**

The low-contrast object specific contrast-to-noise ratio (CNR\textsubscript{LO}) was calculated from CT images of the phantom to evaluate the objective image quality for detectability of tendon. CNR\textsubscript{LO} is a quantitative evaluation index that reflects the image frequency characteristics and the measurement object frequency components and contrast [15]. CNR\textsubscript{LO} was obtained using the following formula, which incorporates the noise power spectrum (NPS):

\[
CNR_{LO} (\tilde{u}) = \frac{ROI_T - ROI_B}{\sqrt{NPS (\tilde{u})}}
\]

\(ROI_T\) and \(ROI_B\) indicate the CT values measured in the extensor tendon-simulating rod and background regions of interest (ROI), respectively, and \(NPS(\tilde{u})\) indicates the NPS at the spatial frequency (\(\tilde{u}\)).

\(ROI_T\) and \(ROI_B\) were analyzed with the free software package ImageJ (National Institutes of Health, Bethesda, MD, USA) [16]. Circular ROIs were placed on the extensor tendon-simulating rod and background to measure the CT value of \(ROI_T\) and \(ROI_B\), respectively (Fig. 2). NPS was analyzed with a radial frequency method using CTmeasure Ver. 0.98f (Japanese Society of CT Technology, Hiroshima, Japan) [17]. Two square ROIs were placed on the background to measure the NPS, and an average NPS was calculated for each tube current and reconstruction parameter (Fig. 2).

The spatial frequency (\(\tilde{u}\)) was calculated using the following formulas:

\[
\tilde{u}^2 = \frac{\int_0^\infty u^2 |S(u)|^2 \, du}{\int_0^\infty |S(u)|^2 \, du}
\]

\[
S(u) = \frac{J_1 (\pi u)}{2\pi u}
\]
ū indicates the most contributing spatial frequency for detectability corresponding to the diameter of the extensor tendon-simulating rod, and $J_1()$ is a first-order Bessel function of the first order, and $d$ is the extensor tendon-simulating rod diameter, and $u$ indicates the frequency. Using Eq. 2 and Eq. 3, the value of $\bar{u}$ was 0.16 in this study.

**Clinical study**

Objective image quality for detectability of tendons in clinical study was assessed using the contrast-to-noise ratio (CNR). The CNR was calculated using the following formula:

$$CNR = \frac{ROI_{tendon} - ROI_{muscle}}{SD_{muscle}}$$  

$ROI_{tendon}$ and $ROI_{muscle}$ indicate the CT values measured in the extensor tendon and muscle ROI, respectively, and $SD_{muscle}$ indicates the standard deviation (SD) value at $ROI_{muscle}$ (Fig. 3).

Furthermore, the coefficient of variation (CV) was calculated as SD of CNR divided by mean of the CNR in all patients.

All clinical images were analyzed the free software package ImageJ (National Institutes of Health, Bethesda, MD, USA) for comparison of reconstruction parameters [16].

**Patient cases**

Example images were extensor tendon 3D images acquired using a workstation (ziostation2; Ziosoft Inc., Tokyo, Japan). The extensor tendons CT images used in 3D images were reconstructed using AIDR3D and AiCE. This case was a 49-year-old man with suspected extensor pollicis longus (EPL) tendon rupture who underwent a CT scan. After that, the rupture of EPL tendon was confirmed during surgery.

**Statistical analysis**

Calculated values are presented as mean ± SD. Friedman test followed by Bonferroni-adjusted Wilcoxon signed-rank test were used to compare the tube currents between 50, 100, 150, 200, and 250 mA and the reconstruction methods between AIDR 3D and AiCE (body, body sharp, brain CTA, and brain LCD). All statistical analysis was performed using the software package easy R (EZR) [18]. A P value of < 0.05 was statistically considered significant.

**Results**
Phantom study

Figure 4 shows the results of CNR<sub>LO</sub> for AIDR 3D and AiCE (body, body sharp, brain CTA, and brain LCD) at different tube currents. The CNR<sub>LO</sub> values for all reconstruction parameters improved as the tube current increased. CNR<sub>LO</sub> value of AiCE brain CTA was higher than other reconstruction parameters at tube currents above 150 mA. Table 1 shows the results of NPS(ü) and difference value between ROI<sub>T</sub> and ROI<sub>B</sub> used in the CNR<sub>LO</sub> analysis. The NPS(ü) values varied with the tube current for all reconstruction parameters. Among them, NPS(ü) of AiCE body sharp was a slight change and smaller value than other parameters.

Table 1

<table>
<thead>
<tr>
<th>CTDI&lt;sub&gt;VOL&lt;/sub&gt; (mGy)</th>
<th>NPS(ü)</th>
<th>Difference values between ROI&lt;sub&gt;T&lt;/sub&gt; and ROI&lt;sub&gt;B&lt;/sub&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AIDR 3D</td>
<td>Body</td>
</tr>
<tr>
<td>2.6</td>
<td>35.0</td>
<td>38.8</td>
</tr>
<tr>
<td>5.2</td>
<td>22.2</td>
<td>26.0</td>
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<td>7.8</td>
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<td>13.7</td>
<td>16.3</td>
</tr>
<tr>
<td>13.1</td>
<td>12.6</td>
<td>15.4</td>
</tr>
</tbody>
</table>

CTDI<sub>VOL</sub> volume computed tomography dose indexes, NPS noise power spectrum, ROI regions of interest, AIDR 3D adaptive iterative dose reduction three dimensional

Clinical study

Figure 5 and 6 show the results of CNR and CV for AIDR 3D and AiCE (body, body sharp, brain CTA, and brain LCD). CNR value of AiCE brain CTA was higher than other reconstruction parameters (P < 0.05). CV value of AiCE brain CTA was lower than other reconstruction parameters. Table 2 shows the results of SD<sub>muscle</sub> and difference value between ROI<sub>tendon</sub> and ROI<sub>muscle</sub> used in the CNR analysis.
Patient extensor tendon 3D imaging

Figure 7 shows 3D images using AIDR 3D and AiCE. All 3D images were processed only with the same color presets on the 3D workstation. On comparing 3D images of AIDR 3D and AiCE, it was evident in difference of extensor tendon depiction. Although the 3D image of AiCE body was reduced noise, extensor tendon depiction was poor. The 3D image of AiCE body sharp and AiCE brain CTA were reduced noise. The 3D image of AiCE brain CTA was identified the extensor tendons and the stump of EPL tendon rupture compared to AiCE body sharp. The 3D image of AiCE brain LCD depicted not only extensor tendons, but also muscles and soft tissue. In consequence, on the 3D image of AiCE brain LCD, the stump of EPL tendon rupture was obstructed by soft tissue.

Discussion

This study evaluated the optimal tube current and reconstruction parameters in extensor tendons 3D CT using AiCE reconstruction. In the phantom study, the CNR$_{LO}$s for all reconstruction parameters improved as the tube current increased. CNR$_{LO}$ value of AiCE brain CTA was higher than other reconstruction parameters. In the clinical study, CNR value of AiCE brain CTA was higher than other reconstruction parameters. We found that extensor tendons 3D CT using AiCE without dose reduction is suitable for improving visualization of extensor tendons, and that AiCE brain CTA parameter is suitable for the depiction of the extensor tendons in 3D CT using AiCE.

In our phantom study, CNR$_{LO}$ of all AiCE parameters were higher value than these of AIDR 3D at all radiation dose. Various authors have indicated that AiCE can improve image quality in the chest, cardiac, and abdomen examinations compared to AIDR 3D [9–11]. Similarly, we considered that AiCE was also effective in improving image quality in tendon examination.

Focusing on the radiation dose, CNR$_{LO}$ values for AiCE brain CTA at CTDI$_{VOL}$ of 7.8 mGy and AIDR 3D at CTDI$_{VOL}$ of 10.5 mGy were similar. It has been reported that DLR enables dose reduction while maintaining image quality, supporting the results of this study [12]. Even for extensor tendons CT, DLR
may offer radiation exposure reduction while maintaining image quality. On the other hand, we suggest that DLR without dose reduction can be expected to offer further improving image quality because CNR_{LO} of AiCE images increased as the radiation dose. Furthermore, we propose that DLR without dose reduction is useful in improving extensor tendons identification in the 3D image and time-saving for 3D image creation because creating 3D images of the extensor tendons, which is a thin and complex structure, is often challenging to identify the extensor tendons with the image quality of conventional reconstruction methods. Therefore, regardless of reconstruction methods such as AiCE and conventional methods, extensor tendons 3D CT is suitable to be performed at tube current of 100–200 mA with reference to the standard protocol (GALACTIC: Guideline for ALL About CT exams: Imaging Concept) by the Japanese Society of Radiological Technology [7].

Focusing on the reconstruction parameters of AiCE, CNR_{LO} improved the most with AiCE brain CTA at 150 mA or more, whereas CNR_{LO} improved the most with AiCE body sharp at 100 mA or less. In the AiCE body sharp, we considered that CNR_{LO}, whose denominator is NPS(ū), was affected by the low NPS(ū) value even at low radiation dose. Thus, AiCE body sharp was able to reduce noise at low dose. However, AiCE body sharp at low radiation dose showed lower CT values difference between tendons and muscles than other reconstruction parameters. Therefore, we must carefully observe the contrast between tendons and muscle in the extensor tendons 3D CT images using AiCE body sharp, which is a soft tissue parameter recommended by the CT manufacturer. On the other hand, the AiCE brain CTA showed higher CNR_{LO} values even 150 mA or less than other reconstruction parameters except AiCE body sharp, and higher CT values difference between tendons and muscles. Therefore, we suggest that CT images reconstructed in AiCE brain CTA is suitable for the extensor tendons 3D CT at any tube current.

In our clinical study, CNR and CV of CNR were compared between reconstruction parameters. CNR was improved with AiCE brain CTA, which showed reducing image noise and high CT value difference between tendons and muscle. The low SD_{muscle} value and the low CT value difference between tendons and muscles using AiCE body sharp were consistent with our phantom study. Therefore, the CT images reconstructed in AiCE body sharp may not be suitable for the extensor tendons 3D CT. CV showed lower values in AiCE brain CTA than other reconstruction parameters. The low CV value can reduce the effect of a patient’s individual difference of tendons CT value and variation in CT scanning. Therefore, this result of low CV values is important for extensor tendons 3D CT affected by small CT values difference between tendons and muscle. We considered that AiCE brain CTA can offer stable 3D images quality of extensor tendons.

Furthermore, we observed that the patient 3D CT image reconstructed with AiCE brain CTA is suitable for extensor tendons 3D CT, consistent with the results of phantom and clinical studies.

This study has limitations. First, we used a single CT scanner in this study. The DLR process may be different for each CT vendors. Additional investigations are needed to evaluate the DLR for tendons 3D CT from different CT vendors. Second, true tatus of tendons in our retrospective study could not be
defined. Therefore, our study did not have verification standard other modalities such as echography and magnetic resonance imaging for comparing the accuracy of the reconstruction parameters.

**Conclusion**

In conclusion, an AiCE technique is a useful for extensor tendons 3D CT. AiCE without dose reduction may be a useful strategy to further improve image quality because creating extensor tendons 3D images is often challenging to identify the extensor tendons in the case of the image quality reconstructed with conventional methods. Our study suggests that the AiCE brain CTA is more suitable for extensor tendons 3D CT than other AiCE parameters.

**Declarations**

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**Competing interests**

The authors have no relevant financial or non-financial interests to disclose.

**Author contributions**

Kunihito Tsuboi contributed to the study design, data collection, and writing and editing of this article; Takamasa Kanbe and Hiroshi Matsushima contributed to the study design, data collection, and reviewing of this article; Yuki Ohtani, Ken Tanikawa, and Masanori Kaneko contributed to the project administration and reviewing of this article. All authors read and approved the final manuscript.

**Ethics approval**

This study was performed in line with the principles of the Declaration of Helsinki. Approval was granted by the Hospital Ethics Committee (June 3, 2022; No.48 and March 29, 2023; No.283).

**Informed consent**

Our Hospital Ethics Committee waived the requirement for individual informed consent due to the retrospective nature of the study.
References


Figures
Figure 1

The phantom with simulated extensor tendon (3 mm)
Figure 2

The experimental setup diagram of ROIs in phantom study. ROI$_T$ and ROI$_B$ indicate CT values at the extensor tendon-simulating rod and background, respectively. Square ROIs were used to measure NPS.
Figure 3

The experimental setup diagram of ROIs in clinical study. $ROI_{tendon}$ and $ROI_{muscle}$ indicate the CT values measured in the extensor tendon and muscle, respectively.
Figure 4

Graph of CNRLO with AiCE (body, body sharp, brain LCD, and brain CTA) and AIDR 3D
Figure 5

Graph of CNR with AiCE (body, body sharp, brain CTA, and brain LCD) and AIDR 3D
Figure 6

Graph of CV with AiCE (body, body sharp, brain CTA, and brain LCD) and AIDR 3D
Figure 7

Extensor tendon 3D images using (a) AIDR 3D, (b) AiCE body, (c) AiCE body sharp, (d) AiCE brain CTA, and (e) AiCE brain LCD. The stump of extensor pollicis longus (EPL) tendon rapture was indicated by white arrow. The soft tissue obstructing identification of the stump of EPL tendon rapture was indicated by red arrows.