Quantification of Intrahepatic Fat Density with Dual Energy CT Imaging - Accuracy analysis by phantom test -

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Aims and objectives

Material decomposition, which is used in dual energy computed tomography (CT), generates CT images using two types of tube voltages and can therefore be used to calculate the density of each base material provided that the mass attenuation coefficients are already known. For this reason, images can be displayed as density images using two basis set materials (hereinafter: “material pair”). This technology is being applied clinically to performing imaging of iodine and fat components using the material decomposition method during spectral CT \cite{1,2}.

The target of this study was fatty liver. To investigate this, we evaluated intrahepatic fat content, a standard for evaluating the degree of fatty liver progression. We performed material decomposition analysis using dual energy CT to precisely evaluate the density measurement values corresponding to fat content using a fat density verification phantom.
Methods and materials

1. Experimental production of the fat density verification phantom

We created a fat density verification phantom that displayed fat density as linear changes with arbitrary intervals by adjusting and mixing a weight ratio of porcine livers and lard with the aim of quantifying intrahepatic fat content (Fig. 1 on page 5, right). As entry of air into sample tissue during mixing would lead to an overall decrease in CT values, mixing was performed in a semi-vacuum state (of or below atmospheric pressure) to sufficiently deaerate the mixture before enclosing it in the spitz. There were a total of 8 patterns used for fat content. These were 0% (liver: 100%), 3%, 5%, 10%, 20%, 30%, 50% and 100% (liver: 0%). Fat density was measured using the volume and weight of each material as an index for evaluation precision. Hereinafter, actual measurement results are referred to as "reference value [#]." The spitz in which materials were enclosed was installed in a 200 mm# cylinder phantom (Kyoto-kagaku, Kyoto, Japan, Fig. 1 on page 5, left) with concentric holes.

2. Basis Set Material Pair calculation

Material decomposition, which is used to calculate density, requires that the mass attenuation coefficients for liver only and fat only, which will become the base materials, be prepared in advance as a basis set material pair.

These mass attenuation coefficients are calculated according to the following procedure. The fat density verification phantom was imaged using dual energy CT to obtain CT images. Scan conditions are shown in Table 1 on page 5. A gemstone spectral imaging (GSI) Viewer fitted with Advantage Workstation was used to output CT values on relevant images for liver only and fat only corresponding to virtual monochromatic images (40-140keV) as "csv files."

The equation defining the CT values was used to inversely calculate the linear attenuation coefficients of liver and fat. Both mass attenuation coefficients, \((\mu/#)_{\text{fat}}\) and \((\mu/#)_{\text{Liver}}\), were then calculated by dividing the above values by reference value [#] (Formula 2). The energy range of calculated values \((\mu/#)_{\text{fat}}\) and \((\mu/#)_{\text{Liver}}\) was 40 - 140 keV (per 1keV) corresponding to virtual monochromatic images.

\[
\text{H.U} = \frac{(\mu_m - \mu_w)}{\mu_w} \times 1000 \quad \text{(Formula 1)}
\]

\[
\mu_m / # = \left(1 + \frac{\text{H.U}}{1000}\right) / # \quad \text{(Formula 2)}
\]

The \((\mu/#)_{\text{fat}}\) and \((\mu/#)_{\text{Liver}}\) values were then entered into AW as the basis set material pair in csv format. Material decomposition analysis, with the GSI Viewer in "general" mode,
was then used to create material density images with both mass attenuation coefficients as base materials. At this point, the brightness of these images was shown not as CT values, but as density [mg/cm$^3$].

Regions of interest of approximately the same area as each material were set up for material density images recomposed with transverse sections and fat density was measured. Below, the actual measurement results are shown as "measured value[#$F$]." Actual measurement results were compared with reference values that were measured in advance in order to verify measurement accuracy (Formula 3). Measurement accuracy was defined as the difference between reference values with measured values.

Measurement Accuracy [%] = (#F - #) / # (Formula 3)
**Fig. 1:** Fat density verification phantom. Fat content was set at ratios of [Fat (0, 3, 5, 10, 20, 30, 50, 100 %)] and a total of 8 materials were created. These materials were mixed in a semi-vacuum state (of or below atmospheric pressure) to sufficiently deaerate them. These materials could be installed concentrically from the center of the fat equivalent phantom (diameter: 200 mm).

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Table 1: Scan Conditions

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**Fig. 2:** Fat density verification phantom [Fat(0, 3, 5, 10, 20, 30, 50, 100 %)] and CT image comparison (a): CT image taken with tube voltage monochromatic images (70keV) (b): Fat density image calculated with basis set material pair as Fat(-Liver) with tube voltage dual energy CT

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Results

1. Image Processing

Fig. 2 on page 10 (a) shows virtual monochromatic images (70keV) and Fig. 2 on page 10 (b) shows fat density images. Materials were arranged such the fat content was 0, 3, 5, 10, 20, 30, 50, 100% when moving clockwise from the 12 o'clock position. Fig. 2 on page 10 (a) shows a general trend towards decreasing CT values as fat content increased. In Fig. 2 on page 10 (b), signal values tended to increase as fat content increased because image signals showed fat density.

2. Calculation of liver and fat mass attenuation coefficients

Fig. 3 on page 10 shows spectral Hounsfield Unit (H.U) curves for liver and fat analyzed with the GSI Viewer. The liver H.U curve exhibited a negative slope, whereas the fat H.U curve exhibited a positive slope. Fig. 4 on page 11 shows \((\mu/\rho)_{\text{fat}}\) and \((\mu/\rho)_{\text{Liver}}\) calculated backward (Formula 1 and 2) from the CT value definitional equation for spectral HU curve (Fig. 3) results. Mass attenuation coefficients for 40-140 keV were considered to be the basis set material pair forming the base materials for material decomposition.

3. Fat density estimation

Fig. 5 on page 12 shows the results of comparison of fat density reference values with measured values according to material decomposition. When the fat weight ratio was 0%, 3%, 5%, 10%, 20%, 30%, 50% and 100%, relative error calculated from Formula 9 was 3.4%, 0.35%, 6.7%, -7.9%, -3.6%, -6.3% and 1.1%, respectively. The general purpose spreadsheet software Microsoft Excel 2013 was used to perform linear regression of fat density reference values and fat density measured values analyzed with GSI Viewer. Results were slope:-0.173 and intercept: -4.053 mg/cm³, indicating a linear function (R = 0.9989, R² = 0.997, P < 0.0001).

Discussion

 Normally, CT values are the only parameters for evaluating images taken using single energy CT scanners and until now, the quantification of fixed materials has been difficult. The density images created in this study from the basis set material pair of liver and fat using dual energy CT bring us closer to solving this problem.
A previous report using fat phantoms with dual energy CT\textsuperscript{[3]} stopped at the correlation with fat content and did not investigate fat density estimation. In the present study, we created density images with liver and fat as the basis set material pair. In these images, liver density was considered to be zero and other values were calculated and converted to fat density values. Thus, theoretically, we calculated fat density as being equal to absolute values. A strong correlation was shown between reference and measured values (R = 0.9989, R\textsuperscript{2} = 0.997, P < 0.0001) in Fig. 5 on page 12, the relative error for each fat content ratio was between -7.9\% and 3.4\%. The calculation of quasi-equivalent fat density values using this method of analysis could form beneficial supplementary information to improve reliability for the quantification of intrahepatic fat content. This study had several limitations. Firstly, it is difficult to apply this method to other types of CT scanners. Secondly, the fat density verification phantom did not imitate the conditions in the human body. However, as attenuation characteristics were similar to those of humans in general, its introduction to the next stage of clinical testing could be justified by optimizing scan conditions. However, some issues related to its clinical introduction remain. These include the method of setting regions of interest and selection of fatty liver cases that can be analyzed with this method. This method of measurement makes it possible to continue interpreting images and making a diagnosis without losing any CT data, which was previously the only type of diagnostic data available. The quantitative evaluation of subject state is also made possible with the physical quantity of density.
Fig. 2: Fat density verification phantom [Fat(0, 3, 5, 10, 20, 30, 50, 100 %)] and CT image comparison (a): CT image taken with tube voltage monochromatic images (70keV) (b): Fat density image calculated with basis set material pair as Fat(-Liver) with tube voltage dual energy CT

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Fig. 3: Results of comparison of fat (0%) and fat (100%) spectral HU curve calculated per 1keV. Values were shown as mean ±SD within the ROI.

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**Fig. 4:** Comparison of mass attenuation coefficients for fat (0%) and fat (100%) spectral curves calculated backward from the Hounsfield Unit definitional equation (Formula 1, 2).

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Fig. 5: Correlative relationship of reference values and measurement values when the fat density verification phantom was imaged with dual image CT. The upper part of the X axis is a weight ratio of liver and fat. The lower part of the X axis shows fat content reference values. Values are shown as mean ± SD within ROI.

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Conclusion

In this study, intrahepatic fat density was estimated using dual energy CT. Porcine livers and lard were mixed in a vacuum to create a uniform material while preventing the entry of air bubbles. The mass attenuation coefficient for each material was then calculated. Performing material decomposition analysis using these materials as the basis set material pair made it possible to evaluate intrahepatic fat density with an error range of between 7.9% and 3.4%. Results suggested that the new addition of "fat density" as an index to CT images used to diagnose fatty liver could aid in the non-invasive diagnosis of degree of progression. As none of the measurement results were mentioned in the performance specifications provided by the manufacturer, their use constitutes equipment-specific performance evaluation, thereby increasing the reliability of the test.
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