Electron density and effective atomic number images generated by dual energy imaging with a 320-detector CT system: A feasibility study

Poster No.: C-0403
Congress: ECR 2014
Type: Scientific Exhibit
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Keywords: Tissue characterisation, Technology assessment, Technical aspects, Computer Applications-General, Image manipulation / Reconstruction, CT-Quantitative, CT, Radiation physics
DOI: 10.1594/ecr2014/C-0403

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Aims and objectives

In radiotherapy treatment planning, the conversion of the CT number (HU) into an electron density is one of the main processes that determine the accuracy of patient dose calculations [1]. However, electron density does not necessarily accurately correlate to CT number, because the CT number depends on the effective atomic number as well as the electron density.

Dual energy CT, in which the subject is scanned at two different energies (tube voltages), can be used to perform material decomposition based on the differences in material absorption coefficients at different energies. Very recently, row data based dual energy analysis using volume scan data has been established by Toshiba Corporation Medical Systems in a 320-detector CT system. It supports reduction of beam hardening artifacts, material decomposition, the creation of iodine maps and virtual non-contrast images, effective atomic number analysis and electron density analysis.

This study was conducted to evaluate the accuracy of the electron densities and effective atomic numbers determined by row data based dual energy analysis on a 320-detector CT system.

Methods and materials

We employed two phantoms to evaluate the accuracy of the electron densities and effective atomic numbers. All CT examinations were performed using a 320-detector CT system (Aquilion ONE Vision, Toshiba Corporation Medical Systems, Tokyo, Japan). Scans were performed ten times in each phantom.

A phantom and CT acquisition for estimation of effective electron density:

We used a tissue characterization phantom Gammex 467 (Gammex Inc., Middleton, WI) that has 16 cylindrical tissue substitute inserts such as lung, liver, brain, adipose, breast, inner bone and cortical bone (Fig. 1). It has also inserts made of solid water and liquid water. The true effective electron densities of these inserts were 0.282-1.693.
Fig. 1: A tissue characterization phantom Gammex 467 that has 16 cylindrical tissue substitute inserts.

References: Diagnostic Radiology, Hiroshima University - Hiroshima/JP

The dual energy CT scan was performed at tube voltages of 80 kV and 135 kV using volume scanning. Exposures of 570 mA and 100 mA were used to minimize noise. The other scanning parameters were a rotation time of 1.0 seconds, 0.5 mm slice thickness, z-coverage value of 40 mm (0.5 mm × 80 slice) and 400 mm field of view. The displayed CTDI was 31.1 mGy.

A phantom and CT acquisition for estimation of effective atomic number:

We used a phantom containing 8 different materials (Tough phantom, Kyoto-Kagaku Co., Ltd of Japan): adipose tissue (SZ-49), muscle (SZ-208), soft tissue (SZ-207), compact bone (BE-T), cortical bone (BE-H), inner bone (BE-N), muscle + adipose (SZ-220), cartilage bone (SZ-160)(Fig. 2). Each symbol in parentheses is the item’s index of Kyoto-Kagaku Co. The true effective atomic numbers were 6.090-13.179.
Fig. 2: A phantom (Tough phantom) containing 8 different materials.

References: Diagnostic Radiology, Hiroshima University - Hiroshima/JP

The dual energy CT scan was performed at tube voltages of 80 kV and 135 kV using volume scanning. Exposures of 800 mA and 200 mA were used to minimize noise. The other scanning parameters were a rotation time of 1.0 seconds, 0.5 mm slice thickness, z-coverage value of 40 mm (0.5 mm x 80 slice) and 240 mm field of view. The displayed CTDI was 55.0 mGy.

Method to determine the electron density and effective atomic number:

The electron densities and effective atomic numbers of each material were calculated by raw data-based decomposition from the dual energy CT data.

In the diagnostic energy range, a linear attenuation coefficient $\mu$ of a material can be describe in terms of photoelectric absorption and Compton scattering exclude the K-edge effects as follows,

$$\mu(E) = \#_{fp}(E) + \#_{fc}(E)$$  \hspace{1cm} (1)
where $E$ is photon energy, $#_p$ and $#_c$ are constants that depend on material and $f_p$ and $f_c$ are constants that depend on $E$ of photoelectric absorption and Compton scattering, respectively.[2-5]. Employing the formula, it is simplified as follows,

$$\mu(E) = f(#_e, Z, E) + f(#_e, E)$$  \hspace{1cm} (2)

where $#_e$ is electron density, $Z$ is effective atomic number.

In dual energy processing, a liner attenuation coefficient can be expressed by two basis materials, as follows,

$$\mu(E) = \mu_1(E)c_1 + \mu_2(E)c_2$$  \hspace{1cm} (3)

where $\mu_1(E)$, $\mu_2(E)$ are known functions of photon energy. The coefficients $c_1$, $c_2$ are independent of energy and vary spatially. By solving the formula (2) and (3), the electron density and the effective atomic number can be obtained.

**Statistical analyses:**

In the electron densities and effective atomic numbers, we calculated the errors between the true and measured values by dual energy CT using the following formula: (measured value - true value) / true value $\times 100$. Correlations between the true and measured values were accessed with the Pearson correlation coefficient. Differences were considered to be statistically significant at $p < 0.05$. We performed all statistical tests with Med-Calc software (version 11.3.7.0, MedCalc, Mariakerke, Belgium).

**Images for this section:**
Fig. 1: A tissue characterization phantom Gammex 467 that has 16 cylindrical tissue substitute inserts.
Fig. 2: A phantom (Tough phantom) containing 8 different materials.
Results

The true and measured electron densities and the errors between the true and measured values are shown in Table 1. The measured electron densities deviated from -2.18 to +5.08 (mean 1.3 ± 1.5%) from true electron densities. Fig. 3 shows the error in the electron density relative to the true value. Measured electron densities highly correlated with true electron densities ($r = 0.997$, $p < 0.001$) (Fig. 4).

![Graph showing error in electron density relative to true value](image)

**Fig. 3**: The error in the electron density relative to the true value.

**References**: Diagnostic Radiology, Hiroshima University - Hiroshima/JP
Fig. 4: Measured electron densities highly correlated with true electron densities ($r = 0.997$, $p < 0.001$).

References: Diagnostic Radiology, Hiroshima University - Hiroshima/JP

The true and measured effective atomic numbers and the errors between the true and measured values are shown in Table 2. The measured effective atomic numbers deviated from -8.62 to +7.74 (mean 3.1 ± 3.2%) from true effective atomic numbers. Fig. 5 shows the error in the effective atomic number relative to the true value. Measured effective atomic numbers highly correlated with true effective atomic numbers ($r = 0.994$, $p < 0.001$) (Fig. 6).
**Fig. 5:** The error in the effective atomic number relative to the true value.

**References:** Diagnostic Radiology, Hiroshima University - Hiroshima/JP
**Fig. 6:** Measured effective atomic numbers highly correlated with true effective atomic numbers ($r = 0.994$, $p < 0.001$).

*References:* Diagnostic Radiology, Hiroshima University - Hiroshima/JP

*Images for this section:*
Table 1: The true and measured electron densities and the errors between the true and measured values.

<table>
<thead>
<tr>
<th>Inset number</th>
<th>Rod type Substitute</th>
<th>Physical Density [g/cm³]</th>
<th>True electron density (Relative to water)</th>
<th>Mean measured electron density (Relative to water)</th>
<th>Error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>LN-300 Lung</td>
<td>0.290</td>
<td>0.282</td>
<td>0.296</td>
<td>5.08</td>
</tr>
<tr>
<td>2</td>
<td>Solid Water</td>
<td>1.019</td>
<td>0.990</td>
<td>0.999</td>
<td>0.95</td>
</tr>
<tr>
<td>3</td>
<td>Inner Bone</td>
<td>1.129</td>
<td>1.082</td>
<td>1.078</td>
<td>-0.38</td>
</tr>
<tr>
<td>4</td>
<td>Solid Water</td>
<td>1.019</td>
<td>0.990</td>
<td>0.996</td>
<td>0.58</td>
</tr>
<tr>
<td>5</td>
<td>Liver</td>
<td>1.094</td>
<td>1.062</td>
<td>1.066</td>
<td>0.39</td>
</tr>
<tr>
<td>6</td>
<td>Bone Mineral</td>
<td>1.146</td>
<td>1.099</td>
<td>1.094</td>
<td>-0.49</td>
</tr>
<tr>
<td>7</td>
<td>LN-450 Lung</td>
<td>0.450</td>
<td>0.435</td>
<td>0.454</td>
<td>4.36</td>
</tr>
<tr>
<td>8</td>
<td>Solid Water</td>
<td>1.019</td>
<td>0.990</td>
<td>0.998</td>
<td>0.80</td>
</tr>
<tr>
<td>9</td>
<td>Brain</td>
<td>1.053</td>
<td>1.049</td>
<td>1.045</td>
<td>-0.34</td>
</tr>
<tr>
<td>10</td>
<td>Adipose</td>
<td>0.941</td>
<td>0.924</td>
<td>0.935</td>
<td>1.19</td>
</tr>
<tr>
<td>11</td>
<td>CB2-50%</td>
<td>1.561</td>
<td>1.471</td>
<td>1.439</td>
<td>-2.18</td>
</tr>
<tr>
<td>12</td>
<td>Solid Water</td>
<td>1.019</td>
<td>0.990</td>
<td>0.993</td>
<td>0.34</td>
</tr>
<tr>
<td>13</td>
<td>CB2-30%</td>
<td>1.334</td>
<td>1.279</td>
<td>1.258</td>
<td>-1.63</td>
</tr>
<tr>
<td>14</td>
<td>True Water</td>
<td>1.000</td>
<td>1.000</td>
<td>1.000</td>
<td>0.00</td>
</tr>
<tr>
<td>15</td>
<td>Breast</td>
<td>0.980</td>
<td>0.957</td>
<td>0.962</td>
<td>0.53</td>
</tr>
<tr>
<td>16</td>
<td>Cortical Bone</td>
<td>1.821</td>
<td>1.693</td>
<td>1.659</td>
<td>-2.02</td>
</tr>
</tbody>
</table>
Fig. 3: The error in the electron density relative to the true value.
**Fig. 4:** Measured electron densities highly correlated with true electron densities ($r = 0.997$, $p < 0.001$).
**Table 2:** The true and measured effective atomic numbers and the errors between the true and measured values.

<table>
<thead>
<tr>
<th>Inset number</th>
<th>Rod type Substitute</th>
<th>True effective atomic number</th>
<th>Mean measured effective atomic number</th>
<th>Error [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Adipose tissue SZ-49</td>
<td>6.090</td>
<td>5.565</td>
<td>-8.62</td>
</tr>
<tr>
<td>2</td>
<td>Muscle SZ-208</td>
<td>7.250</td>
<td>7.344</td>
<td>1.30</td>
</tr>
<tr>
<td>3</td>
<td>Soft tissue SZ-207</td>
<td>7.010</td>
<td>7.054</td>
<td>0.63</td>
</tr>
<tr>
<td>4</td>
<td>Compact bone BE-T</td>
<td>13.179</td>
<td>13.386</td>
<td>1.57</td>
</tr>
<tr>
<td>5</td>
<td>Cortical bone BE-H</td>
<td>11.697</td>
<td>12.005</td>
<td>2.63</td>
</tr>
<tr>
<td>6</td>
<td>Inner bone BE-N</td>
<td>9.141</td>
<td>9.311</td>
<td>1.86</td>
</tr>
<tr>
<td>7</td>
<td>Muscle + Adipose SZ-220</td>
<td>7.130</td>
<td>7.163</td>
<td>0.46</td>
</tr>
<tr>
<td>8</td>
<td>Cartilage bone SZ-160</td>
<td>7.350</td>
<td>7.919</td>
<td>7.74</td>
</tr>
</tbody>
</table>
**Fig. 5:** The error in the effective atomic number relative to the true value.
Fig. 6: Measured effective atomic numbers highly correlated with true effective atomic numbers ($r = 0.994$, $p < 0.001$).
Conclusion

Electron densities and effective atomic numbers can be determined with high accuracy by row data based dual energy analysis with a 320-detector CT system. This may help improve accuracy in radiotherapy treatment planning.

Personal information

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References


