A more accurate method to estimate patient dose during body CT examinations with tube current modulation

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Aims and objectives

BACKGROUND

Tube current modulation (TCM) is a useful dose reducing technique, and substantial dose reduction is achievable without image quality deterioration\(^1\)\(^-\)\(^3\). Modulation of tube current is based on the size, shape, and attenuation of the patient's scanned body part. TCM algorithms are based on angular modulation, z-axis modulation, or a combination of the two. It is important to accurately estimate the radiation dose that patients receive during CT procedures so that any potential risk can be determined and minimized.

The ImPACT (Imaging Performance Assessment of CT Scanners, the scanner evaluation center of the United Kingdom National Health Service) CT patient dosimetry calculator offered by the ImPACT CT scanner evaluation group is a set of commercially available dose simulation tools in which Monte Carlo dose data sets are used to calculate normalized patient dose data from the irradiation of a mathematical phantom\(^4\). This calculator is commonly used for organ doses; however, differences in patient size and variable tube current are not taken into account. Therefore, when CT is performed with TCM, it is possible that actual patient doses may vary from those estimated with the ImPACT calculator. Patient dose using TCM is important to account for the actual body stature and weight of the patient\(^5\),\(^ 6\). Previous study\(^7\) reported that the best estimates of organ dose required raw projection data from the TCM function, however, organ (breast and lung) doses during chest CT were estimated from available data in the DICOM header of each CT image and the those from the raw projection data of the TCM function differed by less than 5%.

PURPOSE

We aimed to establish a more accurate and convenient method for estimating organ and effective doses on CT examinations with TCM using actual patient data from the DICOM header of each CT image and the dosimetry calculator. We also compared longitudinal variations in tube current values between iterative reconstruction (IR) and filtered back projection (FBP) reconstruction algorithms.

Methods and materials

CT Examinations

CT scans were obtained using two helical scanners (Aquilion 64 and RXL, Toshiba Medical Systems, Tochigi, Japan) which have 64 and 16 channels, respectively. The
reconstruction algorithm of the Aquilion 64 was FBP and the reconstruction algorithm of the RXL was IR (AIDR 3D). Both CT examinations were performed using x, y, and z-axis TCM (Volume EC; Toshiba Medical Systems) in a clinical setting. For this retrospective study, we collected consecutive patient data from August to November 2012. In total, 100 consecutive patients were identified who had undergone plane body CT in CT scanners (Aquilion 64 and RXL). Fifty (25 women) of these patients were scanned using the Aquilion 64 with Volume EC (SD, 6; tube rotation speed, 0.5 seconds; maximal X-ray tube capacity, 550 mA; beam collimation, 32 mm; slice thickness, 10 mm; slice interval, 10 mm; beam pitch, 0.828; tube voltage, 120 kV) and 50 other patients (25 women) were scanned on the Aquilion RXL with Volume EC (SD, 6; tube rotation speed, 0.5 seconds; maximal X-ray tube capacity, 500 mA; beam collimation, 16 mm; slice thickness, 10 mm; slice interval, 10 mm; beam pitch, 0.938; tube voltage, 120 kV; reconstruction algorithm, AIDR 3D Mild). Additionally, a scout view was first obtained at 120 kV and 30 mA. The patients were examined in supine position. For each CT scan, the tube currents were acquired from DICOM tube current information on each image from the thyroid (the starting anatomical landmark) to the symphysis pubis (the ending anatomical landmark).

Dose simulation

The ImPACT CT patient dosimetry calculator (version 1.0.4) is a computer application in which Monte Carlo dose data sets are used to calculate normalized patient organ dose data from the irradiation of a mathematical phantom. The mathematical phantom has a fixed z-axis length from the head to pelvis. An Excel (Microsoft, Washington, USA) spreadsheet was utilized as a convenient user interface for estimating organ doses and effective dose using 23 NRPB Monte Carlo-generated scanner data sets. The ImPACT CT scanner evaluation group developed a method to match results from the original 23 scanner data sets to new CT scanners through the use of so-called "ImPACT factors;" these factors are based on $CTD_{air}$, $CTD_{center}$, and $CTD_{peripheral}$ normalized to 100 mAs measured in air and either a standard head or standard body CTDI dose phantom. The ImPACT spreadsheet can be used to determine organ doses and effective doses for a wide range of relevant examination parameters: scanner type, tube voltage, tube current, rotation time, head or body scan, and either scan width and increments for non-helical scans or beam pitch for helical scans. However, our CT scanners performed scanner matching that was selected from the 23 NRPB Monte Carlo-generated scanner data sets, because our CT scanners were not listed in the ImPACT scanner list. The CT scanner measurements $CTD_{air}$, $CTD_{center}$, and $CTD_{peripheral}$ were normalized to 100 mAs using a standard 100-mm pencil dosimeter (Model 9015, 10X5-3CT, Radcal Corp., Monrovia, CA, USA) and entered into the ImPACT spreadsheet along with the acquired scanner data values (Table 1). These simulations used the patient long axis z, with the value of z ranging from 0 to 75 cm, considering the anatomical organ regions (Figure 1).

The conventional method
The conventional method is a fixed tube current simulation using a constant tube current value that is the average tube current over the entire scan length from the thyroid to symphysis pubis. This average is reported by the tube current data extracted from the DICOM header (the slice thickness and slice interval were 10 mm). The ImPACT spreadsheet was populated with the average tube current and calculated the organ doses and effective doses.

**Longitudinal variations method**

The longitudinal variations method used the tube current conversion factors to calculate organ doses, which are the tube current ratios over the entire scan length and each organ region. The longitudinal TCM function was obtained from each patient’s actual CT images via the DICOM header. The DICOM header of each image contains a unique tube current value along with a corresponding table location. The tube current reported in the DICOM header is the average value of the tube current over the rotation used to reconstruct that image. Tube current and table location values for each image were read from the DICOM header of the image data. The average tube currents for 10 organs, including the thyroid, esophagus, lung, breast, liver, stomach, colon, bladder, gonads (the testes in men and the uterus in women instead of the ovaries, because the ovaries are often unclear on plane CT), and kidney were calculated from the DICOM images of each organ region from start to finish. The tube current conversion factors ($F_{TCM}$) were defined as

$$F_{TCM} = \frac{\text{average tube current over each organ}}{\text{average tube current over the entire scan length}}$$

**Fig. 2:** Equation is the tube current conversion factor.

**References:** - Toyoake/JP

The following formula was used to estimate organ doses taking TCM into account:

$$D_{TCM} = F_{TCM} D_{T,R}$$

**Fig. 3:** Equation is the organ dose taking TCM into account.

**References:** - Toyoake/JP

where $D_{TCM}$ is the organ dose taking TCM into account, and $D_{T,R}$ is the organ dose from the conventional method.

The effective dose considering TCM ($E_{TCM}$) was calculated with the following equation:
Fig. 4: Equation is the effective dose considering TCM.

References: - Toyoake/JP

where \( w_T \) is the tissue-weighting factor in ICRP publication 103\(^{(11)} \), \( H_T \) is the equivalent dose, and \( W_R \) is the radiation-weighting factor. \( F_{TCM} \), which represents the bone marrow, skin, bone surface, brain, and salivary glands, was assumed to be 1.0 because the tube current could not read at each region. The \( F_{TCM} \) represents the remainder substituted kidney region because the kidney volume was large and the highest organ dose was in the remainder. Differences of \( F_{TCM} \)s between Aquillion 64 (FBP) and RXL (IR) were statistically evaluated using student's \( t \)-test. And differences of effective dose between the conventional method and longitudinal variations method were statistically evaluated using paired \( t \)-test.

Images for this section:
**Fig. 1:** The scan ranged from 0 to 75 cm for body CT, as shown in the mathematical phantom in the ImPACT CT patient dosimetry calculator (version 1.0.4).

**Table 1:** Scanning parameters for body CT
Results

The mean age of the 100 patients was 63 years old (the age range was 28-88 years old). The average CTDI$_{vol}$ over the entire scan length limited to the region from the thyroid to the symphysis pubis is shown in Table 2. The range of average CTDI$_{vol}$ values over the entire scan length using the Aquilion 64 was 10.0-37.6 mGy (mean, 26.3 mGy) and the those of the Aquilion RXL were 5.6-18.3 mGy (mean, 10.5 mGy).

Table 3 shows the results of the mean F$_{TCM}$ for 10 organs. The mean F$_{AEC}$ values for the breast using the Aquilion 64 (0.76) and RXL (0.73) demonstrated especially low F$_{TCM}$ values among the 10 organs. In contrast, the mean F$_{TCM}$ for the bladder using the Aquilion 64 (1.21) and RXL (1.20) demonstrated the highest F$_{TCM}$ values. These results indicated that the organ doses for bladder and breast estimated by the longitudinal variations method were 20% larger and 25% smaller than those estimated by the conventional method, respectively. Although there were no significant differences except for the esophagus, lung, and remainder, a significant difference was observed between the Aquilion 64 and RXL in the F$_{TCM}$ of all organs for the remainder (student's $t$-test, $p = 0.046$). The CVs for the thyroid and gonads were large using the Aquilion 64 (22% and 54%, respectively) and RXL (16% and 68%, respectively).

Table 4 shows the results of the mean organ doses estimated by the longitudinal variations method. The mean organ doses for the testes using the Aquilion 64 and RXL were 4 and 1 mGy, respectively. These doses were especially low among the 10 organs. In contrast, the mean organ dose for the thyroid using the Aquilion 64 (50 mGy) and the RXL (21 mGy) were the highest observed doses. The range of organ dose ratios (RXL/64) was 0.28-0.45. The ratio calculated by the mean CTDI$_{vol}$ (RXL/64) was 0.399. The CVs for the testes were large using both the Aquilion 64 (91%) and RXL (130%). The CVs for the ovaries were low using the Aquilion 64 (18%) and RXL (30%).

The range of effective doses using the Aquilion 64 with the longitudinal variations method was 11-45 mSv (mean, 30 mSv), while the Aquilion RXL values were 7-21 mSv (mean, 13 mSv) (Figure 2). The ratio calculated from the mean effective doses (RXL/64) was 0.42. Figure 2 shows the effective dose correlations between the conventional method and the longitudinal variations method on the two CT scanners with fitted regression lines. The correlation coefficients ($R^2$) were 0.986 and 0.987 for the Aquilion 64 and RXL, respectively. Although the differences of effective doses were relatively small (mean, 0.7 mSv), there were significantly differences between them (paired $t$-test, $p < 0.05$). The difference in effective doses between the two methods was smaller than those of the organ doses. Mean F$_{TCM}$ values on the Aquilion 64 and RXL were not significantly different for the 10 organs except for the esophagus, lung, and remainder (Table 4). Moreover, in the ratios (RXL/64) of the organ doses, except for the testes, the mean CTDI$_{vol}$ and the mean effective doses were both approximately 0.4. This means
that the longitudinal variations in the tube current ratio over the entire scan length and in each organ region were almost the same for both the IR and FBP algorithms developed by the same manufacturer.

Images for this section:

<table>
<thead>
<tr>
<th>No. of patient (women)</th>
<th>Average CTDIvol over the entire scan</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean (mGy)</td>
</tr>
<tr>
<td>Aquilion 64</td>
<td>50 (25)</td>
</tr>
<tr>
<td>Aquilion RXL</td>
<td>50 (25)</td>
</tr>
</tbody>
</table>

**Table 2:** Average CTDIvol over the entire body CT scan

<table>
<thead>
<tr>
<th></th>
<th>Aquilion 64</th>
<th>Aquilion RXL</th>
<th>Student’s t-test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$F_{TCM}$</td>
<td>CV (%)</td>
<td>$F_{TCM}$</td>
</tr>
<tr>
<td>Thyroid</td>
<td>1.04</td>
<td>22</td>
<td>1.01</td>
</tr>
<tr>
<td>Esophagus</td>
<td>0.85</td>
<td>13</td>
<td>0.81</td>
</tr>
<tr>
<td>Lung</td>
<td>0.89</td>
<td>11</td>
<td>0.84</td>
</tr>
<tr>
<td>Breast</td>
<td>0.76</td>
<td>18</td>
<td>0.73</td>
</tr>
<tr>
<td>Liver</td>
<td>1.07</td>
<td>10</td>
<td>1.06</td>
</tr>
<tr>
<td>Stomach</td>
<td>1.11</td>
<td>12</td>
<td>1.12</td>
</tr>
<tr>
<td>Colon</td>
<td>1.08</td>
<td>7</td>
<td>1.11</td>
</tr>
<tr>
<td>Bladder</td>
<td>1.21</td>
<td>13</td>
<td>1.20</td>
</tr>
<tr>
<td>Gonads</td>
<td>0.94</td>
<td>54</td>
<td>0.84</td>
</tr>
<tr>
<td>Testes (men)</td>
<td>0.64</td>
<td>81</td>
<td>0.39</td>
</tr>
<tr>
<td>Ovaries (women)</td>
<td>1.22</td>
<td>24</td>
<td>1.25</td>
</tr>
<tr>
<td>Remainder</td>
<td>1.04</td>
<td>10</td>
<td>1.08</td>
</tr>
</tbody>
</table>

$F_{TCM} =$ average tube current over each organ/average tube current over the entire scan length

CV = coefficient of variation

**Table 3:** Estimated mean conversion factor, FTCM, from the tube current in the DICOM header
Table 4: Estimated mean organ doses from the longitudinal variations method

<table>
<thead>
<tr>
<th></th>
<th>Aquilion 64</th>
<th>Aquilion RXL</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$D_{TCM}$ (mGy)</td>
<td>CV (%)</td>
<td>$D_{TCM}$ (mGy)</td>
<td>CV (%)</td>
<td>RXL / 64</td>
</tr>
<tr>
<td>Thyroid</td>
<td>50 ± 13</td>
<td>26</td>
<td>21 ± 7</td>
<td>32</td>
<td>0.42</td>
</tr>
<tr>
<td>Esophagus</td>
<td>34 ± 11</td>
<td>31</td>
<td>13 ± 4</td>
<td>29</td>
<td>0.40</td>
</tr>
<tr>
<td>Lung</td>
<td>34 ± 10</td>
<td>29</td>
<td>14 ± 4</td>
<td>30</td>
<td>0.40</td>
</tr>
<tr>
<td>Breast</td>
<td>29 ± 11</td>
<td>37</td>
<td>11 ± 3</td>
<td>28</td>
<td>0.40</td>
</tr>
<tr>
<td>Liver</td>
<td>36 ± 9</td>
<td>26</td>
<td>15 ± 6</td>
<td>38</td>
<td>0.43</td>
</tr>
<tr>
<td>Stomach</td>
<td>38 ± 9</td>
<td>25</td>
<td>17 ± 7</td>
<td>40</td>
<td>0.44</td>
</tr>
<tr>
<td>Colon</td>
<td>31 ± 8</td>
<td>25</td>
<td>14 ± 5</td>
<td>36</td>
<td>0.44</td>
</tr>
<tr>
<td>Bladder</td>
<td>38 ± 7</td>
<td>19</td>
<td>16 ± 5</td>
<td>30</td>
<td>0.43</td>
</tr>
<tr>
<td>Gonads</td>
<td>15 ± 8</td>
<td>56</td>
<td>5 ± 4</td>
<td>75</td>
<td>0.36</td>
</tr>
<tr>
<td>Testes (men)</td>
<td>4 ± 3</td>
<td>91</td>
<td>1 ± 1</td>
<td>130</td>
<td>0.28</td>
</tr>
<tr>
<td>Ovaries (women)</td>
<td>32 ± 6</td>
<td>18</td>
<td>13 ± 4</td>
<td>30</td>
<td>0.40</td>
</tr>
<tr>
<td>Remainder</td>
<td>31 ± 9</td>
<td>29</td>
<td>14 ± 6</td>
<td>41</td>
<td>0.45</td>
</tr>
<tr>
<td>Average CTDIvol</td>
<td>26.3 ± 6.5</td>
<td>25</td>
<td>10.5 ± 3.4</td>
<td>32</td>
<td>0.399</td>
</tr>
</tbody>
</table>

$D_{TCM}$ is the organ dose taking TCM into account
CV = coefficient of variation
Fig. 5: The graph shows the relation between effective doses calculated by the conventional method and longitudinal variations method with a fitted regression line.
Conclusion

The organ doses for bladder and breast on body CT with TCM estimated by the tube current ratios over the entire scan length and each organ regions (the longitudinal variations method) were 20% larger and 25% smaller than those estimated by the average tube current over the entire scan length (the conventional method), respectively. The difference of effective doses between the conventional method and longitudinal variations method was smaller than those of organ doses. The longitudinal variations in the tube current ratio over the entire scan length and in each organ region were almost the same with the IR and FBP reconstruction algorithms developed by the same manufacturer.

Personal information

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