Development of new dosimeter for measuring dose distribution in CT

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Purpose

1. Introduction

As the number of detector rows in CT scanners is increased, the X-ray beam width becomes larger. In general, the beam width of a 64-row multidetector CT (MDCT) scanner is approximately 40 mm and that of an area detector CT (ADCT) scanner is 160 mm. A 64-DAS MDCT scanner, with more detector rows and a larger beam width, permits the entire body to be scanned in approximately 10 s, and an ADCT scanner allows the entire heart to be covered in a single rotation.

The CT dose index (CTDI), dose-length product (DLP), and dose efficiency (DE) are used as indices for measuring the exposure dose of CT systems (reference 1, 2). The most basic value, CTDI, is measured using a cylindrical methacrylate resin phantom and a pencil chamber in combination, with the measured value corrected by the beam width in the calculation. The DLP is calculated by multiplying the weighted CTDI (CTDI_{W}) by the total scan time. In addition, the half-value width (FWHM) of the beam profile is measured by film dosimetry in which ready-pack films or radiochromic films are employed in order to calculate the DE.

However, it has been reported that when the exposure dose of a CT system with a larger beam width is evaluated, the dose is underestimated when a conventional 100-mm pencil chamber is used, and as a result, accurate measurement results cannot be obtained (reference 3). Taking into consideration the evaluation of exposure dose by Monte Carlo simulation such as the Electron Gamma Shower (EGS), it is important to assess the two-dimensional dose distributions in air and the energy spectrum in order to evaluate the exposure dose accurately. However, it is difficult to measure two-dimensional dose distributions easily by film dosimetry.

The present study was therefore conducted in order to develop a new dosimeter for measuring the two-dimensional dose distribution in CT.
Methods and Materials

2. Methods

2.1 Structure of the dose distribution measurement system and dose calibration

2.1.1 Structure of the dose distribution measurement system

A newly developed dose distribution measurement system (PA-32, Toreck, Japan) is shown in Fig. 1 on page 7. The sensor section is mounted on rails with a length of 400 mm. The sensor section can be set at any desired position on the rails (stationary mode) and can also be moved along the rails at constant speed (move mode: 6.7, 10, or 16 mm/s, Fig. 2 on page 7, video clip) using the dedicated software, which runs on a standard Windows personal computer. The dose measurement time can be selected from among 2.5, 5, 10, 30, and 60 s.

A pattern diagram and the external appearance of the radiation receiving (sensor) section of the dosimeter are shown in Fig. 3 on page 8. The radiation sensor section consists of an array of 32 small semiconductor detector elements arranged in a single row. Each element measures 1.175 mm × 2 mm, and the elements are spaced at 1.575-mm intervals. The entire sensor measures 2 mm × 48.825 mm. (It should be noted that the value of 50.4 mm given in the abstract we submitted previously was incorrect due to a calculation error.)

2.1.2 Dose calibration

In general, in order to perform dose calibration for a dosimeter intended for diagnostic applications, the correction value is calculated in a uniform X-ray field generated by a general-purpose X-ray system. In CT systems, however, thick, wedge-shaped bow tie filters made of materials such as Al are employed. In the present study, an ADCT scanner (Aquilion ONE, Toshiba, Japan) was used to generate a uniform X-ray field with the energy spectrum of a CT system. In addition, a semiconductor dosimeter (Xi, Unfors Instruments AB, Sweden) was used as a field dosimeter with calibration performed using a reference dosimeter. The dose distribution in the axial direction in the Aquilion scanner was found to be influenced by heel effects (Fig. 4 on page 9, reference 3). The center of the sensor of the Xi or PA-32 was shifted 35 mm toward the anode from the central axis of rotation, where the dose distribution is maintained at a constant level. Figure 5 on page 10 shows diagrams of the geometric layouts at the time of measurement, and Fig. 6 on page 11 shows the external appearance of the Xi (left panel) and of the PA-32 (right panel) at the time of measurement.

The maintenance mode of the Aquilion ONE scanner was used to perform exposure with the X-ray tube fixed at 0°. The exposure conditions were fixed, with a beam width of 160
mm, the large bow tie filter, and an exposure time of 1.0 s. The tube voltage was varied (80, 100, 120, and 135 kV), and the tube current was adjusted so that the dose read by the Xi was approximately 30 mGy as required.

2.2 Comparison of X-ray beam profiles obtained using the film method and the dose distribution measurement system

Radiochromic films (GAFCHROMIC XR-SP2, lot # A05140904, ISP, USA) and the PA-32 were used to measure the beam profiles in the axial direction in a 16-DAS MDCT scanner (Aquilion 16, Toshiba, Japan) and the measurement results were compared.

2.2.1 Exposure method and conditions

The maintenance mode of the Aquilion 16 scanner was used to generate X-rays with the X-ray tube fixed at 0°. X-rays were generated with various tube voltages (80, 100, 120, and 135 kV), various tube currents (80, 100, 130, and 190 mA), the focus size set to L, various beam widths (8, 16, and 32 mm), an exposure time of 1.0 s, and the large bow tie filter. For the PA-32, measurement was also performed with the focus size set to S.

2.2.2 Measurement by the film method

A sheet of GAFCHROMIC film measuring 10 inches × 12 inches was cut into strips measuring 30 mm in width × 10 inches (approx. 254 mm) in length. A strip of film was placed at the center of rotation with its long side oriented in the axial direction, and the strip was then scanned (Fig. 7 on page 12). After exposure, the strip of film was placed in a light-tight box and stored at room temperature (24°C) for 48 hours.

The strips of GAFCHROMIC film were scanned using a flatbed scanner (ES-10000G, Epson, Japan). The scanner settings were a 16-bit gray scale, a resolution of 300 dpi, and a scan range of 46 mm × 76 mm. The scanned images were saved in TIFF format.

The images were analyzed using ImageJ (NIH, MD, USA. reference 4). An ROI measuring 100 pixels × 900 pixels was placed on the image (Fig. 8 on page 13) to measure the beam profiles in the axial direction. The measured pixel values (net pixel values: PV net) were converted using a dose conversion table (Appendix) relative to the PV net obtained using the Aquilion ONE scanner beforehand.

2.2.3 Measurement using the dose distribution measurement system

Measurement was performed in stationary mode. The sensor section of the PA-32 was placed with its long side oriented in the axial direction, and the PA-32 was set at the center of rotation (Fig. 9 on page 14). In order to improve the measurement accuracy
of the beam profiles, X-rays were generated at 9 points (-40.5, -40.0, -39.5, -0.5, 0, 0.5, 39.5, 40.0, and 40.5) in the axial direction for each beam profile measurement. The nine profiles obtained were then superimposed.

2.3 Measurement of the two-dimensional dose distributions using the dose distribution measurement system

Measurement was performed in move mode. The sensor section of the PA-32 was placed with its long side oriented in the axial direction, and the PA-32 was set with the center of the sensor shifted 172 mm toward the 0° tube position from the center of rotation (Fig. 10 on page 15). The maintenance mode of the 64-DAS MDCT scanner (Aquilion 64, Toshiba, Japan) was used to generate X-rays with the X-ray tube fixed at 0°. X-rays were generated with various tube voltages (80, 100, 120, and 135 kV), various tube currents (50, 75, and 100 mA), various exposure times (25, 40, and 60 s), two types of bow tie filters (small and large), and a beam width of 32 mm (slice thickness of 0.5 mm × 64 DAS).

During exposure, the sensor was moved at a constant speed (6.7, 10, or 16 mm/s) along rails in the x-scan plane direction in order to acquire data over a range of 400 mm (Fig. 11 on page 16, video clip). The output of the sensor (for which energy correction was performed using dedicated software and magnification ratio correction was performed using a homothetic ratio) was converted to the two-dimensional dose distribution at the center of rotation.
Fig. 0: Newly developed dose distribution measurement system (PA-32, Toreck, Japan)

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Fig. 2: A acquisition method has stationary mode and move mode. A video clip is a situation of move mode collection.

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**Fig. 0:** X-ray receiving section of the dosimeter Left: External appearance Right: Pattern diagram (The value of 50.4 mm given in the abstract we submitted previously was incorrect due to a calculation error.)

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Fig. 0: Heel effects in the Aquilion ONE scanner (reference 3) Example of the measured dose profile along the z-axis obtained with a tube voltage of 120 kV and the medium bow tie filter

Fig. 0: Calibration of the dosimeters using ADCT (geometric layouts)

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Fig. 0: Calibration of the dosimeters Left: Xi (Unfors, Sweden) Right: PA-32 (Toreck, Japan)

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**Fig. 0:** Measurement of X-ray beam profiles using the film method (GAFCHROMIC film: XR-SP2, ISP, USA)

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**Fig. 0:** Measurement of X-ray beam profiles using the film method. Image analysis using Image-J ROI size: 100 pixels x 900 pixels

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Fig. 0: Measurement of X-ray beam profiles using the dose distribution measurement system (PA-32, Toreck, JAPAN)

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**Fig. 0:** Measurement of two-dimensional dose distributions using the dose distribution measurement system (PA-32, Toreck, Japan) The sensor section was shifted 172 mm toward the 0° tube position from the center of rotation.

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Fig. 1: Measurement of X-ray beam profiles using the move mode of the PA-32 system

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Results

3. Results

3.1 Dose calibration using the dose distribution measurement system (PA-32)

Figure 1 on page 23 shows the dose calibration results obtained using the PA-32. The horizontal axis of the graph represents the half-value layer of the tube voltages measured by the Xi, the left vertical axis of the graph represents the absolute values of the output values (calibration values) of the PA-32 relative to the dose obtained using the Xi, and the right vertical axis of the graph represents the relative values assuming that the output value of the PA-32 relative to the dose obtained using the Xi at a tube voltage of 120 kV is 1.0.

The half-value layer at tube voltages of 80, 100, 120, and 135 kV measured by the Xi were 4.36, 5.37, 6.20, and 6.70 mmAl, respectively. The calibration values relative to each half-value layers were 20.42, 21.95, 23.36, and 24.38 µGy/digital, respectively. The energy dependency was ±8.5% over the range of energies measured (39.5 keV to 49.5 keV).

3.2 Comparison of X-ray beam profiles between the film method and the dose distribution measurement system (PA-32)

Figure 2 on page 23 shows the beam profiles obtained with a beam width of 32 mm (2-mm slice × 16 DAS) measured using GAFCHROMIC film and the PA-32. Figures 3 on page 24 and 4 on page 25 also show the beam profiles obtained with beam widths of 16 mm (1-mm slice × 16 DAS) and 8 mm (0.5-mm slice × 16 DAS) measured using GAFCHROMIC film and the PA-32. The tube voltage was fixed at 120 kV (5.56 mmAl) and the focus size used was the large focus. Figure 5 on page 26 shows the beam profiles obtained with a beam width of 32 mm at each tube voltage measured using the PA-32. The horizontal axis of the graph represents the distance in the axial direction assuming that the center position of the slice plane is 0, and the vertical axis of the graph represents the relative dose normalized by the maximum dose under different conditions. Tables 1 and 2 show a comparison of the half-value widths calculated from the dose profiles.

For all beam widths, the overall shapes of the beam profiles showed good agreement. In addition, there was almost no variation in the shapes of the beam profiles at all tube voltages. However, as the beam width became smaller, the beam profile obtained using the film method also became narrower due to the effects of the size of the semiconductor elements, showing a difference of 2% to 6% in the half-value width.
<table>
<thead>
<tr>
<th>Focus size</th>
<th>Small/Large</th>
<th>Large</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beam width (slice x DAS)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>32 mm (2 x 16)</td>
<td>40.5 / 42.5</td>
<td>41.4</td>
<td>2.3</td>
</tr>
<tr>
<td>16 mm (1 x 16)</td>
<td>21.9 / 23.2</td>
<td>22.5</td>
<td>3.0</td>
</tr>
<tr>
<td>8 mm (0.5 x 16)</td>
<td>12.8 / 14.1</td>
<td>13.3</td>
<td>5.7</td>
</tr>
</tbody>
</table>

Table 1 Comparison of the half-value widths based in the beam profiles obtained using the radiochromic film and the two-dimensional dose distribution measurement system

<table>
<thead>
<tr>
<th>Focus size</th>
<th>Large</th>
<th>Large</th>
<th>Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube voltage (kV)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>80</td>
<td>42.3</td>
<td>41.4</td>
<td>2.1</td>
</tr>
<tr>
<td>100</td>
<td>42.3</td>
<td>41.4</td>
<td>2.1</td>
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<tr>
<td>120</td>
<td>42.4</td>
<td>41.4</td>
<td>2.3</td>
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<tr>
<td>135</td>
<td>42.5</td>
<td>41.3</td>
<td>2.8</td>
</tr>
</tbody>
</table>

Table 2 Comparison of the half-value widths based on the beam profiles obtained using the radiochromic film method and the two-dimensional dose distribution measurement system

3.3 Measurement of the two-dimensional dose distributions using the dose distribution measurement system

Figure 6 on page 27 shows the two-dimensional dose distributions at tube currents of 50, 75, and 100 mA. The exposure conditions were a tube voltage of 120 kV (5.56 mmAl), a beam width of 32 mm, and the large bow tie filter. The x-axis represents the position in the scan plane direction with the center of rotation assumed to be 0, the z-axis represents the distance in the axial direction with the center position of the slice plane assumed to be 0, and the y-axis represents the dose in air corrected based on the results shown in Fig. 1. The overall shapes of the two-dimensional dose distributions showed good agreement. The doses at point 0 were 19.8 mGy, 29.9 mGy, and 39.8 mGy at tube
currents of 50 mA, 75 mA, and 100 mA, respectively, showing good agreement of the tube current ratios (50:75:100 = 1:1.51:2.01).

Figure 7 on page 28 shows the two-dimensional dose distributions obtained at sensor movement speeds of 6.7, 10, and 16 mm/s using the PA-32. The exposure conditions were a tube voltage of 120 kV, a tube current of 75 mA, a beam width of 32 mm, and the large bow tie filter. The two-dimensional dose distributions showed good agreement, with no dependence on the sensor movement speed.

Figure 8 on page 29 shows the two-dimensional dose distributions acquired with the large (5.56 mmAl) and small (6.83 mmAl) bow tie filters. The exposure conditions were a tube voltage of 120 kV, a tube current of 75 mA, and a beam width of 32 mm. The dose distribution acquired with the large filter showed higher dose levels around the center and a smoother shape horizontally.

Figure 9 on page 30 shows the two-dimensional dose distributions at tube voltages of 80, 100, and 135 kV. The exposure conditions were a tube current of 75 mA, a beam width of 32 mm, and the large bow tie filter. The higher the tube voltage, the higher the dose. The dose ratios between the four tube voltage settings of 80, 100, 120, and 135 kV were 0.47:0.72:1.0:1.21.

4. Discussion

Due to the larger beam width resulting from the introduction of MDCT with a larger number of detector rows, it is important to assess the two-dimensional dose distribution more accurately, but dose evaluation focusing on the conventional CTDI measurement method is limited. In the present study, we have developed a measurement system that permits extremely accurate two-dimensional dose distributions to be obtained easily.

Table 3 shows a comparison of the characteristics of the radiochromic film method and the two-dimensional dose distribution measurement system PA-32. Using the PA-32, measurement can be performed repeatedly by setting the level and the sensor section at specific locations based on CT images.

The two-dimensional dose distribution and the beam width were analyzed in real time when X-ray generation was completed. The energy dependency was ±8.5%, which was higher than that for radiochromic film (±5.0% for the XR-QA type, no data for XR-SP2 type). It was also affected by the absolute size (1.175 mm) of the semiconductor elements. However, when the beam width was 10 mm or more, the difference in the half-value width between the radiochromic film method and the PA-32 was 5% or less, indicating equivalent measurement performance capabilities.
For radiochromic film, on the other hand, analysis can basically be started after 24 hours or more has elapsed. It is also necessary to take into consideration the particular characteristics of the film (which plays the role of the sensor) and the measurement environment, such as light shielding and temperature control. In addition, radiochromic films cannot be recycled and are therefore not environment-friendly.

It should be noted that radiochromic films can be used to perform measurement in phantoms and in water, permitting dose evaluation including scattered radiation. However, as the beam width has increased, the phantoms used for CTDI measurement have become larger and larger. For example, the abdominal phantom measures 320 mm in diameter × 350 mm in length and weighs 34.5 kg (reference 5). Since two-dimensional dose distributions in air can be obtained easily using the PA-32, it is considered that Monte Carlo simulation such as EGS is practical for evaluation of the dose including scattered radiation.

It should be noted that the minimum acquisition time for two-dimensional dose distributions using the PA-32 is 25 s. In modes other than maintenance mode, the measurement environment cannot be ensured easily, which is a future challenge.

<table>
<thead>
<tr>
<th>Factor</th>
<th>PA-32</th>
<th>GAFCHROMIC film</th>
</tr>
</thead>
<tbody>
<tr>
<td>Processing work</td>
<td>Simple</td>
<td>Complicated</td>
</tr>
<tr>
<td>Processing time</td>
<td>Real time</td>
<td>24 hours</td>
</tr>
<tr>
<td>Recycling</td>
<td>Possible</td>
<td>±5.0%*</td>
</tr>
<tr>
<td>Individual differences</td>
<td>Minimal</td>
<td>Yes</td>
</tr>
<tr>
<td>Evaluation of scattered radiation</td>
<td>Not possible**</td>
<td>Possible</td>
</tr>
</tbody>
</table>

*: Based on the catalog data for XR-QA film  
(No data for XR-SP2)

**: Possible with Monte Carlo simulation

Table 3 Comparison of the characteristics of the radiochromic film method and the two-dimensional dose distribution measurement system
**Fig. 0:** Dose calibration of the PA-32 using the Xi as the reference dosimeter

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**Fig. 0:** Comparison of the measured beam profiles between GAFCHROMIC film and the PA-32 (for a beam width of 32 mm)

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Fig. 0: Comparison of the measured beam profiles between GAFCHROMIC film and the PA-32 (for a beam width of 16 mm)

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**Fig. 0:** Comparison of the measured beam profiles between GAFCHROMIC film and the PA-32 (for a beam width of 8 mm)

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Fig. 0: Comparison of the beam profiles between the four tube voltage settings measured using the PA-32 (for a beam width of 32 mm)

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Fig. 0: Two-dimensional dose distributions obtained at various tube currents 120 kV (5.56 mmAl), focus: large, bow tie filter: large, beam width: 32 mm Left upper: Tube current: 50 mA Right upper: 75 mA Left lower: 100 mA

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**Fig. 0:** Two-dimensional dose distributions obtained at various acquisition speeds 120 kV (5.56 mmAl), 75 mA, focus: large, bow tie filter: large, beam width: 32 mm Left upper: Acquisition speed: 6.7 m/s Right upper: 10.0 m/s Left lower: 16.0 m/s

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**Fig. 0:** Two-dimensional dose distributions obtained with the large and small bow tie filters 120 kV, 75 mA, focus: large, beam width: 32 mm Left: Bow tie filter: Large 5.56 mmAl Right: Small 6.83 mmAl

CT system used: Aquilion 64

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**Fig. 0:** Two-dimensional dose distributions obtained at various tube voltages 75 mA, focus: large, bow tie filter: large, beam width: 32 mm Left upper: Tube voltage: 80 kV Right upper: 100 kV Left lower: 135 kV

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Conclusion

5. Conclusion

A dosimeter for measuring the two-dimensional dose distribution using a semiconductor detector has been developed. Compared with the film method, this fully digital method allows real-time dose distribution measurements to be obtained easily and repeatedly.

This dosimeter could be very useful for quality control and also for Monte Carlo simulations in CT that require information about dose distribution.

Appendix

Creating the dose conversion table for radiochromic film using ADCT

In the film method, a table for converting the film density to the dose must be created. Although a general-purpose X-ray system is generally employed, the ADCT scanner was used to create the table for dose calibration as described in subsection 2.1.2.

Figure A-1 on page 34 shows the geometric layout, and Fig. A-2 on page 34 shows the external appearance. The Xi was used as a field dosimeter. A sheet of GAFCHROMIC film (XR-SP2) was cut into pieces measuring 30 mm × 25 mm. The Xi and XR-SP2 film were shifted 35 mm toward the anode from the central axis of rotation, where the dose distribution is maintained at a constant level. The maintenance mode of the Aquilion ONE scanner was used to generate X-rays with the X-ray tube fixed at 0°. The exposure conditions were a beam width of 160 mm, the large bow tie filter, and a tube voltage of 120 kV. Considering that the maximum value is 5 cGy according to the product data (performance table) of the XR-SP2 film, the tube current × time (tube current-time product [mA]) was adjusted in five levels as required. X-rays were generated for the Xi and XR-SP2 film under each set of exposure conditions. After exposure, the GAFCHROMIC film was placed in a light-tight box and stored at room temperature (24°C) for 48 hours.

A flatbed scanner (ES-10000G, EPSON, Japan) was used to scan the films. The scanner settings were a 16-bit gray scale, a resolution of 120 dpi, and a scan range of 40 mm × 40 mm. The scanned images were saved in TIFF format. The images were analyzed using ImageJ (reference 4). An ROI measuring 200 pixels × 200 pixels (13 mm × 13 mm) was placed at the center of each acquired image to measure the pixel values (PV m). In a similar manner, the pixel values in images in which X-rays were not generated (PV bg) were measured. PV net was obtained by subtracting PV bg from PV m.
Figure A-3 on page 35 shows the relationship between PV net and the dose in air. The relationship between PV net and the dose in air was found to be nonlinear. Regression analysis using the least-squares method showed that the regression formula was $y = (5 \times 10^{-5})x^3 + (2.2 \times 10^{-3})x^2 + (4.17 \times 10^{-2})x - 3.06 \times 10^{-2}$ and the coefficient of determination was $R^2 = 0.9997$. 
Fig. 0: Geometric layouts for creating the dose conversion table for the radiochromic film

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**Fig. 0:** Creating the dose conversion table for the radiochromic film

Back: Xi (Unfors, Sweden) Front: XR-SP (IPS, USA)

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Fig. 0: Dose conversion table for GAFCHROMIC film

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