Computed tomography for iodine contrast media detection using energy information measured by a current-mode detector

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Abstract

To exploit the energy information of x-rays in computed tomography (CT), we developed a current-mode detector that gave the energy distribution of the incident x-rays. The CT value obtained for a given material in a phantom depended on the x-ray path length through the phantom. To ensure a constant CT value for a given material, we prepared response functions as a function of the x-rays path length and applied these response functions in the unfolding process. When using response functions that depended on the x-ray path length, the CT values obtained were constant for a given material. In addition, the CT values obtained for iodine contrast media were greater than the values obtained using conventional current CT, especially for higher x-ray tube voltages.

Keywords: Diagnostic X-rays; Unfolding; Energy subtraction method; Contrast media; Filtered X-ray; CT.

1. Introduction

X-ray computed tomography (CT) is a powerful method for detecting cancers, especially when they are marked by a contrast media such as iodine. The absorption of x-rays by iodine is [*]clearly seen above the K-edge of iodine, at 33.2 keV. X-rays with energy much higher than 33.2 keV are less effectively absorbed by iodine than for photons with energy 33.2 keV. When the x-ray tube voltage is high and the x-ray energy spectrum is hard, the effect of the iodine contrast media is difficult to observe using the conventional current measurement method. This phenomenon is called the beam hardening effect, and the same effect occurs when a subject is thick. After passing through the thick subject, higher energy x-rays dominate and the absorption effect by iodine is obscured [1].

By using information on the x-ray energy, the beam hardening effect can be avoided. As shown in Ref. [2], by exploiting the x-ray events at energies above and below the K-edge of iodine, the absorption effect by iodine is clearly observed, despite the difficulties induced by the x-ray tube voltage and the subject thickness. This method is called energy subtraction (ES) CT.

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The conventional method of measuring x-ray energy, however, takes too long for clinical CT. To make ES CT practical, we invented a new detector that measures x-rays as a current and gives the energy distribution of the x-rays [3]. This detector is called a “transXend” detector. The transXend detector consists of several segment detectors stacked along the direction of x-ray incidence, as shown in Fig. 1. The transXend detector requires a response function to unfold the current data and generate the energy distribution of the incident x-rays. The response function can be obtained using an x-ray simulation code such as EGS5 [4]. It may also be obtained experimentally by measuring x-rays transmitted through several iodine contrast media of known thicknesses.

We performed a preliminary CT measurement on a cylindrical acrylic phantom with an iodine region at the center using a transXend detector with CsI(Tl) scintillator segment detectors. ES CT values obtained from the iodine region are much greater than those obtained using conventional current CT [5]. The ES CT values from acrylic regions, however, depended on the acrylic thickness through which the x-rays passed. We did not observe this variation in CT values in the acrylic region when the energy of each x-ray was measured using a conventional CdZnTe detector [2].

To ensure that the CT values remain constant for a given material, we prepared response functions for varying thicknesses of the phantom through which the x-rays pass. In this paper, we discuss our method of preparing the response functions and how to apply these response functions in the unfolding method.

2. Experiment

2.1 Experimental setup

X-rays were generated by an x-ray tube (TRIX-150S, Toreck Co. Ltd., Japan) and sequentially conditioned using a 2 mm thick Al filter, a Pb collimator (5 mm thick, 5 mm diameter), and a 100 μm thick La filter. In this x-ray beam was placed a rectangular acrylic phantom with four iodine regions filled by thinned iodine tincture with various thicknesses. After transiting the phantom, the x-rays beam was measured using the transXend detector with CsI(Tl) segment detectors, as shown in Fig. 2. The CsI(Tl) segment detectors are made of a CsI(Tl) scintillator array with photodiodes (S5668-11, Hamamatsu Photonics K. K., Japan). The CsI(Tl) scintillators were 2 mm wide, 5 mm high, and 1.175 mm thick. For experiments, the first two photodiodes with scintillators on them were connected together and behaved as a segment detector No. 1. In the same way, we had six segment detectors with twelve CsI(Tl) schintillators and photodiodes. The current measured by the segment detectors was amplified using a six-channel current preamplifier (IPA-6, Raytech Corp., Japan) and was read out simultaneously using a voltage-frequency converter (VFCT-8S4, Laboratory Equipments Corp., Japan). The position of the acrylic phantom, as well as the timing of current readout, was computer-controlled using LabVIEW software.

We varied the thickness of the acrylic phantom from 7 to 47 mm by adding 10 mm thick acrylic slabs, which allowed us to measure the current values for the different acrylic thicknesses and thereby obtain the response functions. For CT measurements, we replaced the rectangular phantom by a cylindrical acrylic phantom 40 mm in diameter. The cylindrical acrylic phantom had a 10 mm diameter hole at the center to accept iodine tincture thinned by water (30 μm in 10 mm water) and was mounted on a precision x-θ stage.

2.2 Response functions

The energy ranges of interest are just above and below the K-edge of iodine. To study the x-rays energy distribution for tube voltages of 50, 65, and 80 kV, we define six energy ranges as follows: E_1, 20–27 keV, E_2, 28–33 keV, E_3, 34–39 keV, E_4, 40–50 keV, E_5, 51–65 keV, and E_6, 66–80 keV. The number of events in each energy range Y_i (i = 1,6) and the measured current by each segment detector I_j (j = 1,6) are related by

$$\begin{pmatrix} I_1 \\ I_2 \\ \vdots \\ I_6 \end{pmatrix} = \begin{pmatrix} R_{11} & R_{12} & \cdots & R_{16} \\ R_{21} & \ddots & & \\ \vdots & & & \\ R_{61} & \cdots & & R_{66} \end{pmatrix} \begin{pmatrix} Y_1 \\ Y_2 \\ \vdots \\ Y_6 \end{pmatrix}. \qquad (1)$$

Here, R_{ij} (i,j = 1,6) are the response functions. Unfolding Eq. (1) by the SAND II code, the energy distribution of the incident x-rays Y_i is obtained [6].

To obtain response functions that correspond to various acrylic thicknesses, we plotted the measured current values as a function of acrylic thickness for each segment detector, and fit a semi-log curve to the data. The semi-log fit allows us to estimate the current values for the acrylic thicknesses that we did not measure experimentally.

For the initial guess of the x-ray energy distribution, the calculated energy distributions Y_i^0 are generated for acrylic thicknesses ranging from 7 to 47 mm in 1 mm steps, and the iodine thicknesses from 0 to 70 μm in 1 μm steps, using Eq. (2) of Ref. [2]. With the CT image obtained from the current measurements (e.g., obtained by the segment detector 1) the acrylic thickness d through which the x-rays passed is calculated, and then this response function for the acrylic phantom thickness d mm is used in the unfolding process. With the initial guesses of the x-ray energy distribution for fixed x-rays path length d but changing iodine thickness, an x-ray energy distribution with the smallest SAND II error is taken as the most probable x-ray energy distribution.

2.3 CT images and CT values

CT images of 40 mm diameter acrylic phantoms, obtained using the conventional current measurement method and the ES method, are shown in Fig. 3 for the case of 65 kV x-ray tube voltage. The profiles at the center of the phantom are shown in Fig. 4 for x-ray tube voltages of 50, 65, and 80 kV. When the response function obtained for the acrylic thicknesses corresponds to the x-ray path length, the CT values in the acrylic region become nearly constant, which represents an improvement over previous work [5]. For a tube voltage of 50 kV, the difference in CT values between the iodine and the acrylic regions is nearly the same for the current and the ES CT measurement. In this experiment, the current CT values for tube voltages of 50 and 65 kV tube happened to be nearly the same. The ES CT values, however, stayed nearly constant, independent of the x-ray tube voltage, whereas the conventional current CT suffers from the beam hardening effect. In particular, the ES CT value is twice as big as the current CT value at a tube voltage of 80 kV. This result shows that the ES CT is insensitive to the beam hardening effect, even when the energy information is obtained using the transXend detector.

3. Conclusion

The energy subtraction (ES) method for x-ray CT is shown to be insensitive to the beam hardening effect, which is a distinct advantage over the conventional current measurement CT method. To make the ES CT method practical, the current-mode detector “transXend” was developed, which measures the energy distribution of the incident x-rays. The transXend detector required knowledge of the response functions, which must be obtained as a function to the thickness of the subject through which the x-rays pass. Knowledge of the response functions allows the derivation of the x-ray energy distribution. The path length of the x-rays through the subject under investigation is obtained by conventional current CT, which is always available when using the transXend detector. When using the response functions, which are dependent on the subject thickness, the CT values of the same material become nearly constant.

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Figure captions

Figure 1 Schematic drawing of a transXend detector.

Figure 2 Schematic drawing of the experimental setup.

Figure 3 CT images reconstructed using (a) current and (b) energy subtraction data. The x-ray tube voltage was 65 kV.

Figure 4 CT values for the current and energy subtraction CT at the center of CT images in Fig. 3. The x-ray tube voltages are shown in the figure.

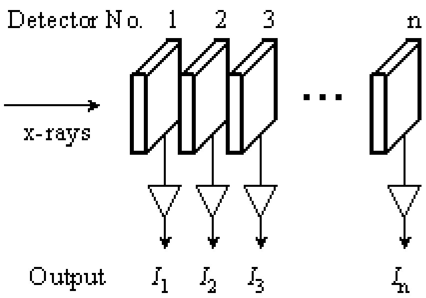


Figure 1

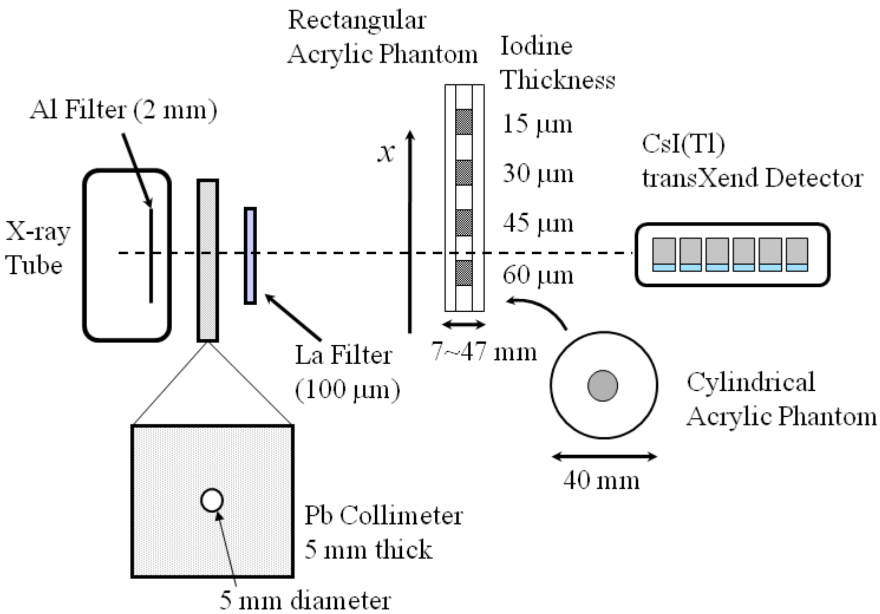

Rectangular
Acrylic Phantom
Iodine
Thickness
Al Filter (2 mm)
15 µm
30 µm
45 µm
60 µm
x
CsI(Tl)
transXend Detector
X-ray
Tube
La Filter
(100 µm)
7~47 mm
Cylindrical
Acrylic Phantom
40 mm
Pb Collimeter
5 mm thick
5 mm diameter

Figure 2

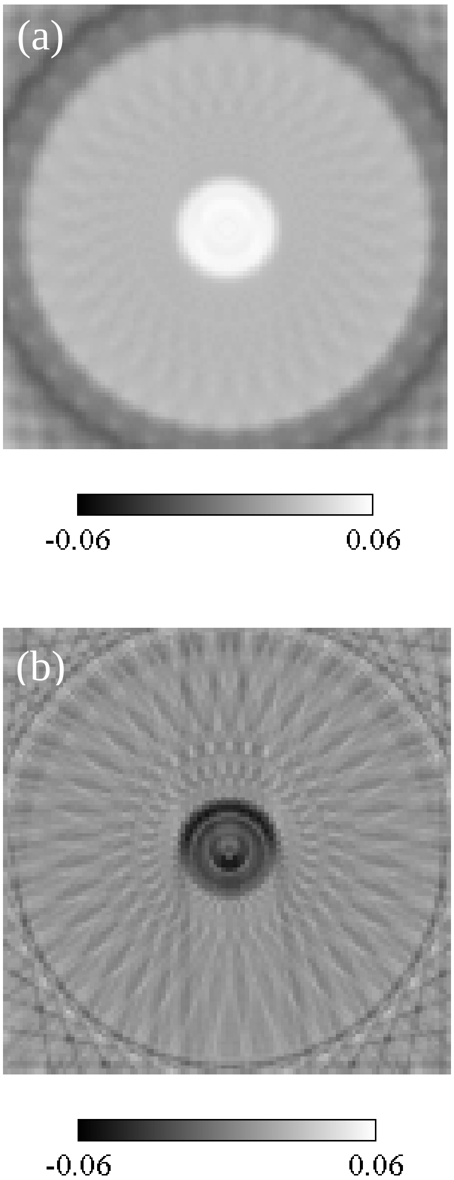
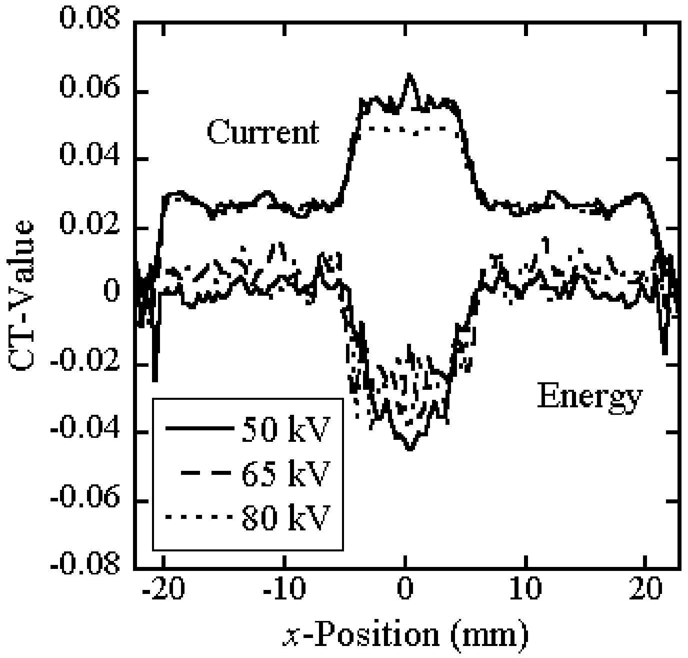


Figure 3



0.08
0.06
0.04
0.02
0
-0.02
-0.04
-0.06
-0.08
CT-Value
Current
Energy
50 kV
65 kV
80 kV
-20
-10
0
10
20
x-Position (mm)

1

2

3 Figure 4