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Energy-resolved computed tomography with a response-function-less transXend detector

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A “transXend” detector measures X-rays as electric current and yields an X-ray energy spectrum after analysis. Response functions are necessary for the analysis and are previously estimated using material details of the X-ray detector. The detector specifics, however, are not always available to users. Here, a “response-function-less” transXend detector is described that relies on transmission measurements of X-rays that passed through known basis materials. The validity of the method is verified by obtaining effective atomic numbers for nine resins.

Keywords: X-ray; computed tomography; energy-resolved; current measurement; response function; effective atomic number

1. Introduction

X-ray computed tomography (CT) is a powerful modality often used to image tumours inside the human body. In hospitals, X-rays are measured as electric current without considering their energy spectra. Linear attenuation coefficients of materials are higher for low-energy X-rays; thus, high-energy X-rays dominate after passing through the human body, and the average energy changes according to the path length. That is, the average energy is high/low when the path length is long/short. As a result, the linear attenuation coefficient in the centre of the body has a small value. This effect is called beam hardening [1]. To avoid this effect, information regarding X-ray energy is required. Therefore, X-ray energies in CT measurements are analysed in photon-counting CT (PC-CT), dual-energy CT (DE-CT), and energy-resolved CT (ER-CT).

PC-CT measures the energy of each X-ray. The number of X-rays is very large, $10^9$ mm$^{-2}$s$^{-1}$ or $10^6$ mm$^{-2}$s$^{-1}$, when arriving at a detector after they pass through the air or a thick body [2]. To reduce the number of X-rays to be measured by one detector-readout system, a PC-CT uses an X-ray detector made of many small-pixel detectors [3]. Also,
the X-ray energies are sorted into six to eight bins to reduce the processing time of each pixel detector. Still, the counting rate is too low for practical uses [4].

DE-CT is used to image the human body with two different X-ray tube voltages, which are typically 80 kV and 140 kV for 53.3 keV and 71.0 keV X-ray energies, respectively [5]. Moreover, the average energies change with the inspection point in the patient’s body because they are measured as electric current in DE-CT. The DE-CT device is used clinically with the support of analysis algorithms.

We have been developing ER-CT with a “transXend” detector [6]. A stacked-type transXend detector consists of several segmented detectors aligned in the direction of the X-ray incidence angle, as shown in Figure 1 of Ref. [6]. A transXend detector measures X-rays as electric current and yields an incident energy spectrum via an analysis that uses response functions for each segmented detector. With an ER-CT using the transXend detector, the absolute value of the linear attenuation coefficient of a material is obtained as a function of X-ray energy. The effective atomic number and the electron density are then estimated from the linear attenuation coefficient [7].

The stacked-type transXend detector was developed for measurements of X-rays that are collimated like a pencil beam. For future clinical use, we developed planar-type transXend detectors that use two different metal-ribbon filters and a two-dimensional detector, such as a flat panel detector (FPD) shown in Refs. [8, 9]. Planar-type transXend detectors have had shortcomings such as larger spatial resolution than that of the FPD and the absorption of X-rays which passed through a phantom (in place of a human body). When we use 0.5 mm wide metal-ribbon filters to make lattice type absorbers as shown in Ref. [8], the dimension of the pixel of the transXend detector was 1.0 mm×1.0 mm, while, as written in section 2.4, the pixel size of the employed FPD was 48 μm×48 μm.
To make use of the FPD spatial resolution, and to avoid wasting X-rays passing through a phantom, we developed another type of planar-type transXend detector that had variable filters placed at the output of the X-ray tube [10].

For planar-type transXend detectors with either ribbon or variable filters, a FPD response function is still required to estimate the X-ray energy spectrum. Because the typical FPD has a scintillator plate in addition to the array of silicon pixels, many details about the scintillator material are necessary to estimate the response function. These details are not always available for FPDs in hospitals.

Here, we describe a method for constructing a planar-type transXend detector with variable filters that does not need a response function (i.e., it is “response-function-less”) for a practical ER-CT at a hospital. Initially, electric currents induced by X-rays that passed through two basis materials are measured. Look-up tables (LUTs) are then prepared by interpolating the currents. Previously, the LUTs were estimated by calculations using response functions [11]. Then, the ER-CT measurements are performed for a phantom consisting of various resins. A planar-type transXend detector with four filters or channels is used. The X-ray attenuation by the phantom is reproduced with attenuations by the two basis materials having suitable thicknesses. This is a material decomposition method, which yields a linear attenuation coefficient as a function of X-ray energy and the effective atomic number of the material. Finally, we compare the effective atomic number ($Z_{eff}$) with a previous method for validation.

2. Methods

A flow chart for the present and conventional method is shown in Figure 1. In both methods, LUTs for the electric currents are prepared as functions of the thicknesses of
the basis materials, polypropylene (PP) and polyvinyl chloride (PVC): the effective atomic numbers of inner organs are between the ones of PP and PVC. The combination of PP and PVC thicknesses, \( t_{PP} \) and \( t_{PVC} \), respectively, which reproduces the measured electric current \( I_i(k, l) \) at the measurement point \((k, l)\) is then used for the material decomposition. Here, \( i \) is the \( i \)-th channel of the transXend detector, \( k \) is the \( k \)-th pixel of the FPD in the horizontal direction, and \( l \) is the \( l \)-th angle of the phantom, as shown in Figure 2. Once the LUTs are obtained, both the present and conventional methods use a material decomposition process that yields a linear attenuation coefficient and the effective atomic number.

### 2.1 Present method of LUT preparation

X-ray transmission measurements were performed for every number and combination of PP and PVC plates ranging over 0–4 and 0–5, respectively. Hence, there were 30 measurements in total, and the unit thicknesses of the plates were 1.0 cm and 0.51 cm, respectively. The electric current measurements were performed for four channels. Interpolations of the electric current were performed over 0.1 cm and 0.01 cm steps over the PP and PVC thicknesses, respectively. The LUTs for electric currents were thus prepared as functions of PP and PVC thicknesses for each channel of the transXend detector as \( I_i^P(t_{PP}, t_{PVC}) \).

### 2.2 Conventional method of LUT preparation

In the conventional method, electric currents induced by X-rays after passing through various thicknesses of the basis materials are estimated by calculations, as reported in Ref. [10]. Initially, the X-ray energy spectrum \( Y_0(E) \) was calculated via
Birch’s formula [12]. Based on $Y_0(E)$, the spectrum for the $i$-th channel, $Y_i(E)$, was calculated from the Beer-Lambert law [13]. The response function $R(E)$ was estimated via the GEANT4 Monte Carlo code, using the thickness and composition of a scintillator plate [14]. Details of the scintillator plate are given in section 2.4. The electric currents, $I_i^c(t_{PP}, t_{PVC})$, were calculated for variable thicknesses $t_{PP}$ and $t_{PVC}$, with 0.1 cm and 0.01 cm steps, from,

$$ I_i^c(t_{PP}, t_{PVC}) = a \int Y_i(E) R(E) \exp \left\{ - \frac{\mu_{PP}(E)}{\rho_{PP}} \cdot \rho_{PP} t_{PP} - \frac{\mu_{PVC}(E)}{\rho_{PVC}} \cdot \rho_{PVC} t_{PVC} \right\} dE, $$  \hspace{0.5cm} (1)

where $\mu_{PP}(E)/\rho_{PP}, \mu_{PVC}(E)/\rho_{PVC}$ and $\rho_{PP}, \rho_{PVC}$ are the mass attenuation coefficients and densities of PP and PVC, respectively. The gain constant $a$ is cancelled when the ratio of electric currents induced by X-rays that passed through the air to those passed through the basis materials is calculated. As above, the LUTs were estimated as functions of PP and PVC thicknesses.

2.3 Material decomposition

In a CT measurement, X-rays pass through the phantom at measurement angle $l$ and are detected by the $k$-th pixel of the FPD. This is measurement point $(k, l)$, and the measurements are performed with the $i$-th channel ($i=1, 4$). The electric current $I_i(k, l)$ is given by,

$$ I_i(k, l) = I_{0,i} \cdot \exp\left\{ - \int \left( \sum_{j=1}^{n} \mu_j(E) t_j(k, l) \right) dE \right\}, $$  \hspace{0.5cm} (2)

where $I_{0,i}$ is the electric current for the $i$-th channel when the X-rays passed through the air, and $\mu_j(E)$ and $t_j(k, l)$ are the linear attenuation coefficient and the thickness of the $j$-th material in the phantom, respectively.

In the material decomposition method, the attenuation term is given by the combination of attenuations in the PP and PVC basis materials,
\[ \sum_{j=1}^{n} \mu_j(E)t_j(k,l) = \frac{\mu_{PP}(E)}{\rho_{PP}} \cdot \rho_{PP} t_{PP}(k,l) + \frac{\mu_{PVC}(E)}{\rho_{PVC}} \cdot \rho_{PVC} t_{PVC}(k,l), \]  
where \( \rho_{PP} t_{PP}(k,l) \) and \( \rho_{PVC} t_{PVC}(k,l) \) are given as CT data.

### 2.4 Experiments

The experimental setup is shown in Figure 2. The X-ray tube (TRIX-150S, Toreck Co., Ltd., Yokohama, Japan) had a W target with an incident angle of 22° and a 1 mm thick Be filter. An additional 2 mm thick Al filter was installed to reduce the low energy X-rays. The tube voltage and current were 120 kV and 2.4 mA, respectively.

To control the X-ray spectra, we used Cu filters with thicknesses of 0, 0.1, 0.2, and 0.3 mm for channels 1–4, respectively. The calculated effective X-ray energies after passing each filter were 57.2, 61.7, 64.9 and 67.4 keV, respectively. These filters were placed on a 1 mm thick polymethylmethacrylate (PMMA) rotating disk that was located at the output of the X-ray tube.

The FPD (Remote RadEye2, Teledyne Rad-icon Imaging, Santa Clara CA, USA) had a 1024×1024 array of 48 \( \mu m \times 48 \mu m \) silicon photodiode pixels and a 48.2 mm×48.2 mm sensitive area. A 50 \( \mu m \) thick Gd\(_2\)O\(_2\)S (GOS) scintillator plate absorbed the X-rays and emitted photons that were detected by the photodiode pixels. To reduce fluctuations in the pixel values, the values were summed from pixel 567 to pixel 596 in the vertical direction.

A 1 mm thick tungsten slit with a 4 mm high opening was placed 70 cm from the X-ray tube output. As noted above, electric current was measured for X-rays that passed through various thicknesses of PP (0–4 plates) and PVC (0–5 plates) placed between the rotating wheel and the tungsten slit to determine LUTs. Examples of experimental LUTs are plotted in Figure 3 as functions of PP and PVC thicknesses for channel 1.
The PP and PVC plates were removed when ER-CT measurements were performed for the 30 mm diameter PMMA (C₅O₂H₈:6.54) phantoms, where the value 6.54 is the effective atomic number Z_{eff}. Two phantoms, A and B, had four 5 mm diameter holes, in which four different resin rods were inserted with various Z_{eff} [7]. In phantom A, polyethylene (PE, C₂H₄:5.49), polypropylene (PP, C₃H₆:5.49), polyoxymethylene (POM, CH₂O:7.02), and polytetrafluoroethylene (PTFE, C₂F₄:8.47) rods were inserted. In phantom B, acrylonitrile butadiene styrene (ABS, C₁₅H₁₇N:5.79), polycarbonate (PC, C₂H₂:6.32), polyvinylidene difluoride (PVDF, C₂H₂F:7.96), and polyvinyl chloride (PVC, CH₂CHCl:14.04) rods were inserted. CT measurements were performed with 1 degree steps of the rotating phantom.

2.5 Analysis

2.5.1. Density distributions for PP and PVC

The X-ray attenuation by the phantom at measurement point (k, l) was reproduced by the PP and PVC with thicknesses of t_{PP}(k, l) and t_{PVC}(k, l), which minimize the value S(k, l),

\[ S(k, l) = \sum_{i=1}^{4} \left[ I_i(k, l) - l_i^r(t_{PP}(k, l), t_{PVC}(k, l)) \right]^2 , \]  

(4)

where I_i(k, l) is the electric current for point (k, l) in the i-th channel. \( l_i^r(t_{PP}(k, l), t_{PVC}(k, l)) \) is the electric current value in the LUTs for the i-th channel by the present (p) or the conventional (c) methods, where the superscript r is for p or c, respectively. Two sets of ER-CT data are obtained as \( \rho_{PP} t_{PP}(k, l) \) and \( \rho_{PVC} t_{PVC}(k, l) \) for point (k, l).
Images for the PP and PVC density distributions, $\rho_{PP}(x,y), \rho_{PVC}(x,y)$, respectively, are obtained via image reconstructions using the maximum-likelihood expectation-maximization method [15]. Density distribution images obtained by the present method are shown in Figure 4 (a) and (b), and those obtained by the conventional method (not shown) are similar. The linear attenuation coefficients and $Z_{eff}$ obtained by the conventional method are not explicitly given below.

### 2.5.2. Linear attenuation coefficients

Using the mass-attenuation coefficients of PP and PVC reported by the National Institute for Standards and Technology [16], the linear attenuation coefficient $\mu^P(x,y,E)$ for each pixel $(x,y)$ in Figure 4 (a) and (b) is given by,

$$\mu^P(x,y,E) = \frac{\mu_{pp}(E)}{\rho_{PP}} \cdot \rho_{PP}(x,y) + \frac{\mu_{pvc}(E)}{\rho_{PVC}} \cdot \rho_{PVC}(x,y). \quad (5)$$

### 2.5.3 Effective atomic numbers

By using the same method reported in Ref. [7], the effective atomic number $Z_{eff}$ for each pixel in Figure 4 (a) and (b) is estimated from the linear attenuation coefficient in Equation (5). Generally, the coefficient is the product of the atomic number density $N \text{ (cm}^{-3})$ and the photon-atom cross section $\sigma(Z,E)$ [16],

$$\mu(Z,E) = N \cdot \sigma(Z,E). \quad (6)$$

To estimate $Z_{eff}$ for various resins, the values of $\sigma(Z,E)$ were interpolated by a natural cubic spline functions for $Z_{eff}$ with 0.01 steps, as shown in Figure 3 of Ref. [7], because $\sigma(Z,E)$ was prepared for integer $Z$. The $Z_{eff}$ for the material at $(x,y)$ was found by fitting $\mu^r(x,y,E)$ with $N \cdot \sigma(Z_{eff},E)$, and determining the minimum $S_j(x,y,Z_{eff})$ by the least-squares method,

$$S(x,y,Z_{eff}) = \sum_{k=1}^n \{ \mu^r(x,y,E_k) - N \cdot \sigma(Z_{eff},E_k) \}^2, \quad (7)$$
where $E_k$ is the $k$-th X-ray energy over the range 30–90 keV, with 0.5-keV intervals.

$Z_{eff}$ values estimated by the present method are shown in Figure 5. The $Z_{eff}$ of each resin was obtained from the average value over the 25 × 25 pixel regions of interest. Summarized $Z_{eff}$ results from the present and the conventional methods are plotted in Figure 6 (a) and (b), respectively. The error bars are twice the values of the standard deviations of the pixel values in the regions of interest.

3. Results and discussion

In Figure 4 (a) and (b), the densities around the resin rods are lower because of air gaps between the PMMA and the resin rods. The pixels that cover the air gap thus consist of air, PMMA, and resin regions, and the average density of these three regions is lower than that of surrounding pixels.

On the other hand, the $Z_{eff}$ values of air regions in Figure 5 (a) and (b) do not show obvious difference from the ones of resins: the $Z_{eff}$ of the air is 7.78, and is similar to the ones of the surrounding resins.

Figure 6 (a) shows the $Z_{eff}$ obtained by the present method. The $Z_{eff}$ of various resins agreed excellently with a theoretical line, which shows the proportionality between the theoretical and measured values, except PVC. The values for higher $Z_{eff}$, however, fall below the theoretical line slightly. The $Z_{eff}$ value of PVC is taken as an extreme example of this tendency.

The deviations of the $Z_{eff}$ values of resins from the theoretical line may be related to low electric current induced by X-rays which passed high $Z_{eff}$ resins such as PVC: when the electric current induced by the X-rays has small value, it tends to be affected...
by the electric noise of the FPD. The electric noise is not negligible comparing to the
electric current induced by X-rays and the measured electric current is higher to some
extent than the one it should be. This higher electric current brings lower linear
attenuation coefficient and results in small $Z_{\text{eff}}$.

In Figure 6 (b), the experimental $Z_{\text{eff}}$ values of the resins estimated by the
conventional method are greater than the theoretical values, except for PVC. The
deviations of $Z_{\text{eff}}$ from the solid line are larger than those in Figure 6 (a), which
indicates that the response function used by the conventional method was not very
accurate; the thickness of the GOS scintillator plate might not be correct.

In contrast, the $Z_{\text{eff}}$ value of PVC was on the theoretical curve in Figure 6 (b). This
agreement is the result of using PP and PVC as basis materials in this analysis; the
material decomposition method cannot yield a smaller $Z_{\text{eff}}$ than that of PP and a larger
$Z_{\text{eff}}$ than that of PVC. To re-estimate the $Z_{\text{eff}}$ of PVC, we performed a material
decomposition using PP and potassium (K:19) basis materials. The estimated $Z_{\text{eff}}$
values are shown in Figure 7, where the $Z_{\text{eff}}$ of PVC shows excellent agreement with
the calibration line.

Because the $Z_{\text{eff}}$ values obtained by both the present and conventional methods are
on the calibration lines, the $Z_{\text{eff}}$ values of unknown materials can be estimated with
these lines. The least-squares correlation factors for the calibration lines obtained for the
present and conventional methods with K are 0.999 and 0.998, respectively. These
values show that the present response-function-less method, with no information for the
detector, is comparable with the conventional method that used a detector response
function for constructing a planar-type transXend detector.
3. Conclusions

Without using detailed information on a planar-type X-ray detector, ER-CT can be performed by using X-ray transmission measurements through two basis materials with various thicknesses. The effective atomic numbers for various resins that span those of human tissues were estimated accurately. Our next study is the application of this method to a practical CT device, equipped with a FPD, for measurements of a human-sized phantom.

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References


Figure captions

1 Figure 1 Flow charts of the present (P) method used here and the conventional (C) analysis method. P- and C- look up tables (LUTs) are prepared by the two methods, respectively.

2 Figure 2 Schematic top and the side views of the experimental setup.

3 Figure 3 Electric currents induced by X-rays that passed through polypropylene (PP) or polyvinyl chloride (PVC) in channel 1. Symbols are measured data and the lines are interpolated.

4 Figure 4 Density distribution images of polymethylmethacrylate phantoms (a) A and (b) B for the basis materials polypropylene (PP, left) and polyvinyl chloride (PVC, right), respectively.

5 Figure 5 Effective atomic number distribution images for phantoms (a) A and (b) B. Refer to the text for the resin names. The rectangles are regions of interest for estimating effective atomic numbers.

6 Figure 6 Summaries of estimated effective atomic numbers obtained by (a) present and (b) conventional methods. Refer to the text for the resin names. Solid lines show the proportionality between the theoretical and measured values. Dashed lines are least-squares fits of the estimated values. Error bars are twice the values of the standard deviations in the regions of interest in Figure 5.
Figure 7 Summary of estimated effective atomic numbers obtained by the conventional method with the polypropylene and potassium basis materials. Refer to the text for the resin names. Solid lines show the proportionality between the theoretical and measured values. Dashed lines are least-squares fits of the estimated values.
Figure 1

Present

Measurements
X-rays passed
PP plates 0–4
PVC plates 0–5

Interpolation
Electric currents
PP 0.1 cm intervals
PVC 0.01 cm intervals

Conventional

Channel
1~4

Calculations
X-ray spectra
Response functions

Electric currents
PP: 0–4 cm, 0.1 cm step
PVC: 0–2.55 cm, 0.01 cm step

P-LUTs

CT measurements

C-LUTs

Materials decomposition

Density distribution images

Linear attenuation coefficients

Effective atomic numbers
Figure 2
Figure 3
Figure 4
Figure 5
Figure 6
Figure 7