Nuclear Instruments and Methods in Physics Research A 787 (2015) 121–124

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

Effective atomic number measurement with energy-resolved X-ray computed tomography

Ikuo Kanno*, Yoshiki Yamashita, Masashi Kimura, Fukutaro Inoue

Department of Nuclear Engineering, Graduate School of Engineering, Kyoto University, Katsura, Nishikyo, Kyoto 615-8530, Japan

ARTICLE INFO

Available online 28 November 2014

Keywords:
X-ray computed tomography
Energy-resolved
Effective atomic number

ABSTRACT

The effective atomic number, Z_{eff} , is measured by the ratio of linear attenuation coefficients at two different X-ray energies obtained by monochromatic X-ray computed tomography (CT). However, monochromatic X-rays are available in synchrotron facilities only. By defining narrow energy ranges in energy-resolved CT using a current mode "transXend" detector, Z_{eff} is measured for sugar and K_2HPO_4 solutions, as well as for water and acrylic. The experimental Z_{eff} values obtained for water and acrylic were in excellent agreement with the theoretical values. The experimental Z_{eff} values obtained for the sugar and K_2HPO_4 solutions had larger errors.

1. Introduction

X-ray computed tomography (CT) is one of the most commonly employed techniques for finding tumors in the human body. CT measurements performed in hospitals measure X-rays as electric current and give the CT images as a distribution of the linear attenuation coefficient, which is averaged by the energy spectrum of the X-rays.

The energy spectrum of X-rays after passing through a patient becomes harder than that before entering into the patient. This phenomenon is called the beam hardening effect. [1] Because of the beam hardening effect, the linear attenuation coefficient of a material changes as functions of material thickness and X-ray tube voltage.

To avoid the beam hardening effect, it is desirable to use the energy information of X-rays. That is, energy-resolved CT. Measuring the energy of each X-ray is an ideal method for energy-resolved CT. There is, however, not currently an X-ray detector able to cope with the counting rate in the CT measurements. [2]

To overcome the counting rate problem, we have developed a new X-ray detector system, called a "transXend" detector, which measures X-rays as electric current and outputs the energy distribution of incident X-rays after analysis. [3] Previously studied applications of the transXend detector include measurement of the iodine contrast agent [4], performing material distinction between iodine and calcium [5], and investigation of the possibility of low dose exposure CT using a high K-edge contrast agent [6].

Other than the applications described above, we have previously conducted energy-resolved CT with the transXend detector for the estimation of effective atomic number, Z_{eff} [7]: commonly, Z_{eff} is measured with using two monochromatic X-rays. [8] Z_{eff} of acrylic and aluminum was successfully estimated with the errors of within 1%. In this study, energy-resolved CT is applied to the estimation of Z_{eff} of materials with atomic numbers that are lower and higher than that of water.

2. Experiments

2.1. transXend detector

The transXend detector consists of several segment detectors aligned along the direction of X-ray incidence, as shown in Fig. 1. Details of the operating principle of the transXend detector are described in Ref. [3]

In this study, four Si(Li) detectors are used as segment detectors. A tin absorber with the thickness of 58 μm is placed in front of the third segment detector to change the response functions. The dimensions of the Si(Li) detectors are 10 × 10 × 1 mm^3. The Si(Li) detectors are operated at room temperature without applying bias voltage. [9] The electric circuits used for transXend detector are described in Ref. [3].

2.2. Response function estimation

Various concentrations of sugar and K_2HPO_4 solutions were used to demonstrate the estimation of Z_{eff} values that were both less and greater than that of water (theoretical value: 7.42). The experimental setup for response function measurements is shown

* Corresponding author. Tel./fax: +81 75 383 3911.
E-mail address: kanno@nucleng.kyoto-u.ac.jp (I. Kanno).

http://dx.doi.org/10.1016/j.nima.2014.11.072
0168-9002/

in Fig. 2. An additional filter made of 2-mm-thick aluminum is placed at the exit of X-ray tube (TRIX 150 S, Toreck Co. Ltd., Japan). The X-rays are collimated by a 5-mm-diameter × 5-mm-thick lead plate. A transXend detector with a 2-mm-wide collimator is placed at the end of X-ray path. Between the X-ray tube and the transXend detector, various concentrations of solutions and acrylic with the thickness from 10 to 40 mm with 10 mm interval are placed on a precision stage (SGSP26-150, Sigma Koki Co. Ltd., Japan). With the movement of the precision stage, X-rays after passing through various concentrations of solutions and acrylic with variety of thicknesses are measured. Response functions are estimated following the method described by Imamura et al. [4].

2.3. CT measurements

For CT measurements, a 30-mm-diameter acrylic phantom is used. As shown in Fig. 2, the acrylic phantom has a 5-mm-diameter hole at its center, and four holes with the same diameter 12 mm from the center. Measurements of sugar and K_2HPO_4 solutions were performed independently. In the measurements of sugar solutions (gum syrup), deionized water is placed in the center hole and one of the outer holes as a reference. The other three outer holes are filled with air, 50% and 100% gum syrup. For the measurements of K_2HPO_4 solutions, 3, 6, 9 and 12% solutions are placed in the outer holes and deionized water is placed in the center hole as a reference.

CT measurements are performed using first generation CT, that is, by translation and rotation of the phantom. The translation step is 0.4 mm and the rotation angle is 5 degrees. The X-ray tube voltage and tube current are 120 kV and 2.4 mA, respectively. The measurement time is 1 s for each measurement point.

The energy ranges used in the unfolding process are shown in Table 1. In E_2 and E_4, energy ranges are narrowed to have quasi-monochromatic X-rays. Using the number of X-rays in E_2 and E_4, CT images that show linear attenuation coefficient distributions at each energy are obtained. Figs. 3 and 4 show these results for the acrylic phantom with sugar and K_2HPO_4 solutions, respectively.

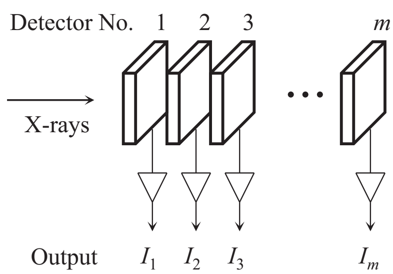

Fig. 1. Schematic drawing of the transXend detector.

Table 1
Assigned energy ranges for response function estimation and CT analysis.

	E_1	E_2	E_3	E_4	E_5	E_6
keV	15.0–30.0	30.0–30.5	30.5–60.0	60.0–60.5	60.5–100.0	100.0–120.0

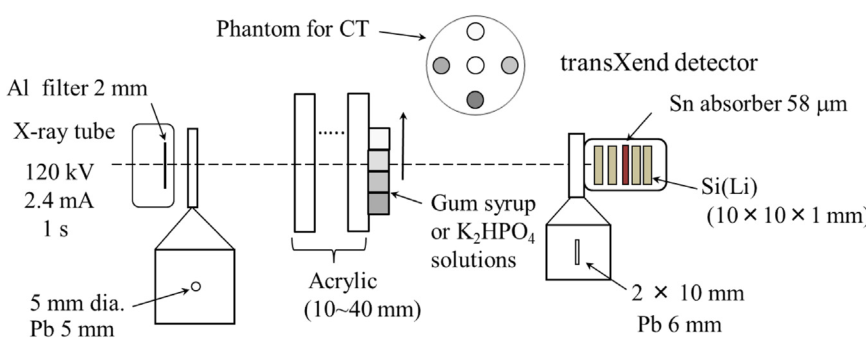

Fig. 2. Experimental setup for response functions and CT measurements.

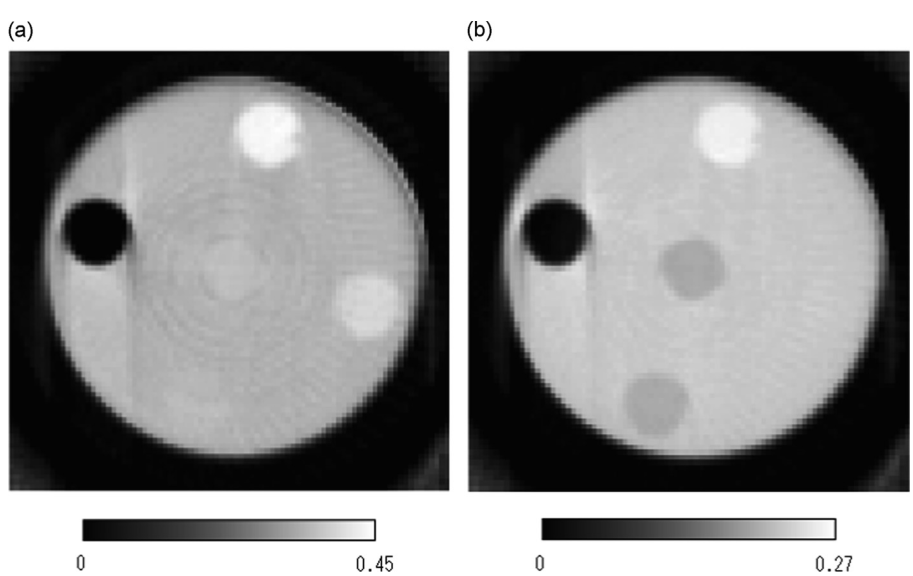

Fig. 3. CT images of the acrylic phantom with sugar solutions made of the X-rays in the energy ranges (a) E_2 and (b) E_4, respectively.