DUAL-ENERGY X-RAY CT BY COMPTON SCATTERING HARD X-RAY SOURCE

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Abstract

We are developing a compact Compton scattering hard X-ray source by the X-band linac and YAG lasers at Nuclear Professional School, University of Tokyo. The compact hard X-ray source can produce tunable monochromatic hard X-rays for 10 - 40 keV. The monochromatic hard X-rays are very useful in large fields of medical and biological sciences. We are planning to carry out dual-energy X-ray CT, which enables us to obtain 3D distribution of effective atomic number $Z_{\rm eff}$ and electron density $\rho_{\rm e}$ in a matter. The hard X-ray source has an advantage in the dual-energy X-ray CT. The X-ray energy can be changed quickly by introducing a fundamental-frequency and a second-harmonic-frequency lasers. It is indispensable to change the X-ray energy quickly for medical imaging, but it is very difficult to achieve the quickness with a large SR light source and others. The information on the atomic number and electron density will be used for radiation treatment planning as well as for identification of materials in a nondestructive test. We examined applicability of the dual-energy X-ray CT for low to medium Z elements ($Z \leq 38$) by considering the X-ray energy profile generated by the Compton scattering hard X-ray source.

INTRODUCTION

Monochromatic hard X-rays are required in large fields of medical and biological applications. Intense hard X-ray is generated by SR light sources, but most of SR light sources are too large for widely applications. Therefore, a compact hard X-ray source is needed for wide use of monochromatic hard X-ray. We have developed a compact Compton scattering hard X-ray source [1, 2] using an X-band linac as presented in Fig. 1. The compact hard X-ray source can produce tunable monochromatic (1 to 10 % energy spread rms) hard X-rays for 10 - 40 keV. We are planning to perform dual-energy X-ray CT using monochromatic hard X-ray, which enables us to obtain cross sectional image of a material based on effective atomic number $Z_{\rm eff}$ and electron density ρ_e. Experiments for the dual-energy X-ray CT has been carried out utilizing SR light sources to measure electron density in biological materials [3, 4]. The electron density in a biological material was measured in agreement within 1 % of the theoretical one [3]. We will use the dual-energy X-ray CT for atomic number analysis in a material. For instance, the information on atomic number distribution in a tumor will contribute to treatment planning for advanced radiotherapy. Atomic number images in a plant are needed in plant physiology. In a nondestructive test of radioactive waste, we need to identify elements of a material. So far, the dual-energy X-ray CT has been performed for biological materials which consist of light elements of $Z \leq 20$. To apply the dual-energy X-ray CT for wide-range atomic numbers, we have carried out a numerical simulation and examined the applicability of the method by considering the X-ray profile of the compact hard X-ray source. Furthermore, we are planning to apply the compact hard X-ray source for micro vessel angiography and protein structural analysis.

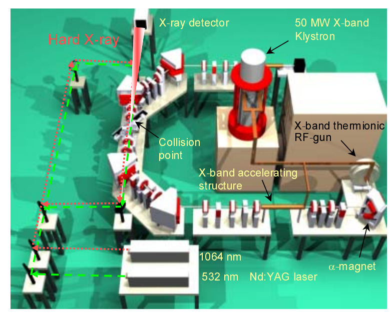

Figure 1: Schematic drawing of the compact hard X-ray source based on Compton scattering.

DUAL-ENERGY X-RAY CT

Theoretical Background

Effective atomic number $Z_{\rm eff}$ and electron density $\rho_{\rm e}$ are obtained by linear attenuation coefficients of a material using two monochromatic X-rays with different energies. A linear attenuation coefficient μ of a material is approximately written as a function of atomic number Z and X-ray energy E using a formula proposed by Jackson and Hawkes [6], as follows;

$$\begin{aligned}\mu(Z,E) \simeq& \rho\frac{N_{\rm A}}{A}Z\{4\sqrt{2}Z^4\alpha^4(\frac{mc^2}{E})\phi_0\sum_{nll'}f_{nll'} \\ &+\sigma_{\rm KN}+\frac{Z(1-Z^{b-1})}{Z'^2}\sigma_{\rm SC}^{\rm coh}(Z',E')\} \\ =& \rho_e(Z^4F(Z,E)+G(Z,E))\end{aligned} \tag{1}$$

where, ρ is mass density, $N_{\rm A}$ is Avogadro's number, A is atomic mass, $f_{nll'}$ is the collection terms for photoelectric absorption cross section, $\sigma_{\rm KN}$ is the Klein-Nishina cross section and $\sigma_{\rm SC}^{\rm coh}$ is the coherent scattering cross section of the standard element Z' at energy of $E' = (Z'/Z)^{1/3}E$.

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0-7803-8859-3/05/$20.00

In the equation, parameter b is proposed to be 0.5 and the standard element is Oxygen [6]. When linear attenuation coefficients are measured for two energies E_1 and E_2, one can extract effective atomic number Z_{eff} and electron density ρ_{e} by solving following equations;

$$Z^4 = \frac{\mu(E_2)G(Z,E_1) - \mu(E_1)G(Z,E_2)}{\mu(E_1)F(Z,E_2) - \mu(E_2)F(Z,E_1)}, \tag{2}$$

$$\rho_{\text{e}} = \frac{\mu(E_1)F(Z,E_2) - \mu(E_2)F(Z,E_1)}{F(Z,E_2)G(Z,E_1) - F(Z,E_1)G(Z,E_2)}. \tag{3}$$

The effective atomic number Z_{eff} is defined for a compound or a mixture as;

$$Z_{\text{eff}} = \left(\sum_i q_i Z_i^k\right)^{1/k} \tag{4}$$

where q_i is the fractional electron content of ith element in the compound or the mixture and the parameter $k = 4$.

This dual-energy method is limited by the K-edge energy of a material because the equation (1) can not be applied below K-edge energy. We will operate the compact hard X-ray source as electron beam energy is 35 MeV and the wavelength of the laser is 1064 nm and 532 nm. In this situation, the maximum X-ray energies are 21.9 keV and 43.8 keV. The X-ray energy should allow us to identify elements up to $Z = 38$. Energy spread $\Delta E/E$ of the monochromatic hard X-ray generated by SR is in the order of 10^{-4}, but the energy spread in the compact hard X-ray source is expected to be 1 to 10 % (rms), which is dependent on the collimator angle [2]. The energy spread of the X-ray is negligible with SR light sources, but in the case of the Compton scattering X-ray source the energy spread affects the accuracy of atomic number identification.

To examine the applicability of the dual-energy X-ray CT with the compact hard X-ray source, we have performed a numerical simulation for low to medium Z elements ($Z \leq 38$). We adopt linear attenuation coefficients of materials listed in the photon cross section database [7] in the simulation. The geometry of the dual-energy X-ray CT system in the simulation is shown in Fig. 2. We assumed a point light source and the thickness and width of the sample is 1 mm and 20 mm, respectively. In this case,

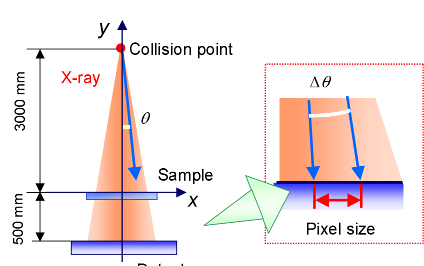

Figure 2: Schematic drawing of the dual-energy X-ray CT system using the compact monochromatic hard X-ray source.

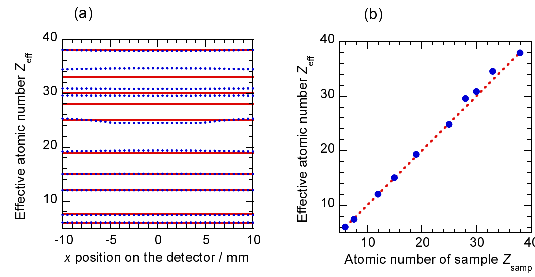

Figure 3: (a) Effective atomic number Z_{eff} on each pixel of the detector. The solid circles indicate identified effective atomic number Z_{eff}. (b) Average of the effective atomic numbers.

X-ray photons are collimated at 3.3 mrad. It is noted that the X-ray energy of the Compton scattering X-ray source is dependent on the scattering angle. Thus, the X-ray energy is unique on each pixel of the 2D detector. When pixel size is 0.5 mm, $\Delta\theta$ is less than 0.2 mrad and the energy spread in the pixel is in the order of 0.1 %. This small energy spread in the pixel should improve accuracy of the dual-energy analysis. Effective atomic numbers obtained by the linear attenuation coefficients for two energies on each pixel of the detector are shown in Fig. 3(a). Average of the Z_{eff} is plotted as a function of atomic number of sample Z_{samp} in Fig. 3(b). The accuracy of estimated effective atomic number $\Delta Z/Z$ is less than 3 % (rms) except for $Z = 25$ and 33. We confirmed that atomic number can be identified up to $Z = 38$ using 21.9 keV and 43.8 keV X-rays with enough accuracy even energy spread of the monochromatic X-ray is 1 to 10 %. The limitation of this method is due to K-edge energy of the material.

CT Simulation

A numerical CT simulation has been carried out with low to medium Z elements. We assumed CT system as already shown in Fig. 2 with cylindrical samples. The diameter of the sample is 20 mm and the pixel size of the detector is 0.1 mm. First, light elements of $Z = 13, 15$ and 19 with water as presented in Fig. 4(a) is tested. Reconstructed cross sectional images of the sample based on linear attenuation coefficients are obtained for two energies. Solving the equations (2) and (3), atomic number in the image is derived from linear attenuation coefficients based images. Two-dimensional images based on effective atomic number distribution in the sample and the reconstructed image are shown in Fig. 4. Atomic number distributions of both images at $y = 0$ are compared in Fig. 5(a). As shown in Fig. 5(a), atomic number in the material is well analyzed for light elements of $Z = 13, 15$ and 19 with $\Delta Z/Z_{\text{samp}}$ is 2.1, 5.0 and 7.2 % (rms), respectively. The poor accuracy for the element of Z=19 is caused by the reconstruction method and it will be improved.

This analysis can be applied to medium Z elements up to $Z = 38$. We have simulated CT image by assuming a sample consists of medium Z elements shown in Fig. 6(a). As shown in Fig. 6(b), the medium Z element of $Z = 38$ is also identified with $\Delta Z/Z_{\mathrm{samp}}$ is 2.7 % (rms). The atomic number distribution of the reconstructed image at $y = 0$ is compared with that of the sample in Fig. 5(b). We have found that the dual-energy X-ray CT can be used to identify medium Z elements ($Z \leq 38$) in a material using the Compton scattering X-ray source with X-ray energies of 21.9 keV and 43.8 keV.

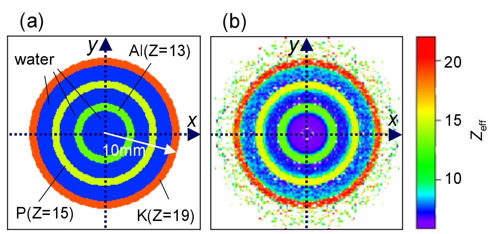

Figure 4: (a) Atomic number distribution in the sample. (b) Atomic number distribution in the reconstructed image.

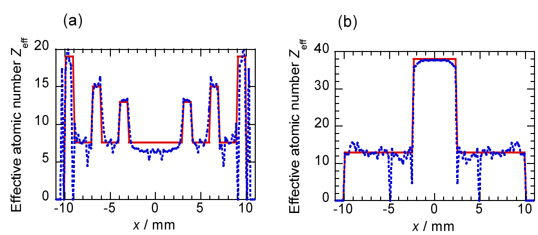

Figure 5: Atomic number distributions at $y = 0$ for sample and reconstructed images in (a) Fig. 4 and (b) Fig. 6. The dotted line indicates effective atomic number Z_{eff} and the solid line indicates atomic number of the sample.

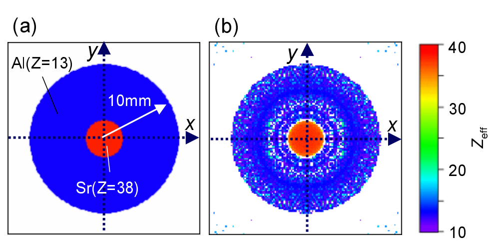

Figure 6: (a) Atomic number distribution in the sample. (b) Atomic number distribution in the reconstructed image.

APPLICATIONS

As already mentioned above, the dual-energy X-ray CT should be a powerful tool for identification of elements in a material. Atomic number distribution measurement will contribute to treatment planning in advanced radiotherapy. We will reveal the availability of atomic number distribution in a tumor using the Monte-Carlo code "EGS4" for a treatment planning. In the biological application, a combination of the dual-energy X-ray CT and the neutron radiography is planned. Neutron radiography enables us to obtain water images in a living plant [5]. The combination of the dual-energy X-ray CT and the neutron radiography is useful to study movement of specific elements in a living plant. The hard X-ray source has an advantage for the dual-energy X-ray CT. The X-ray energy can be changed quickly by introducing a fundamental-frequency and a second-harmonic-frequency lasers. The switching time of the two lasers is planned to be 40 ms. It is needed to change the X-ray energy quickly for the dual-energy X-ray CT in medical and biological applications. Furthermore, the compact hard X-ray source will be applied to micro vessel angiography and protein structural analysis. The micro vessel, diameter of 25 μm, is already observed by SR light. Recently, micro vessel angiography has been performed using X-ray tube combined with the HARP camera in a small laboratory. The micro vessel angiography system will be constructed utilizing the compact X-ray source combined with the HARP camera.

SUMMARY

We have examined the applicability of the dual-energy X-ray CT using the compact hard X-ray source by a numerical simulation. Low to medium Z elements up to Z=38 are well identified with X-ray energies of 21.9 keV and 43.8 keV. Though the energy spread of monochromatic X-ray is 1 to 10 %, the X-ray energy profile depends on the scattering angle. Therefore, the energy spread of X-ray in a pixel is in the order of 0.1 %. The small energy spread in a pixel is an advantage of the Compton scattering X-ray source for the dual-energy X-ray CT. In addition, the X-ray energy can be changed quickly by introducing the two lasers. The quickness is very important advantage of the X-ray source for the dual-energy X-ray CT in medical and biological applications.

ACKNOWLEDGEMENT

The work on development of the X-ray source is performed in the national project of gDevelopment of Advanced Compact Acceleratorsh in Japan and partially supported from Research Program on Development of Innovative Technology in Japan Science and Technology Agency. The study on applications of the X-ray source is supported by the Japanese Ministry of Education, Culture, Sports, Sciences, and Technology and the Japanese Ministry of Health, Labor and Welfare.

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