Original Article

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Analysis of Beam Hardening of Modulation Layers for Dual Energy Cone-beam CT

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Dual energy cone-beam CT can distinguish two materials with different atomic compositions. The principle of dual energy cone-beam CT based on modulation layer is that higher energy spectrum can be acquired at blocked x-ray window. To evaluate the possibility of modulation layer based dual energy cone-beam CT, we analyzed x-ray spectrum for various thicknesses of modulation layers by Monte Carlo simulation. To compare with the results of simulation, the experiment was performed on prototype cone-beam CT for 50～100 kVp with CdTe XR-100T detector. As the result of comparing, the mean energy of energy spectrum for 80 kVp are well matched with that of simulation. The mean energy of energy spectrum for 80 and 120 kVp were increased as 1.67 and 1.52 times by 2.0 mm modulation layer, respectively. We realized that the virtual dual energy x-ray source can be generated by modulation layer.

Key Words: Dual energy cone-beam CT, Beam hardening effect, Modulation layer, Monte Carlo simulation

Introduction

There are several methods to employ dual energy cone-beam CT such as rapid voltage switching, double-layer detector, and sequential acquisition methods.[1-3] Recently, Faby et al. have proposed the multi-energy CT, namely MECT, which was equipped with photon counting detector.[4]

The concept of modulation layer based dual energy cone-beam CT is that the high- and low-energy spectra can be acquired with a single scan by blocking half of x-ray window with modulation layer. In this system, various energy spectra can be generated with various thicknesses of modulation layers, as similar as bowtie filters at current cone-beam CT system, without any additional x-ray tubes and detectors. Another advantage of modulation layer based dual energy cone-beam CT is that monochromatic images which are often necessary to check patients' position can be acquired easily by removing modulation layer.[5]

The high-energy spectrum can be acquired with only a single x-ray tube and detector by blocking the x-ray window with the modulation layer made of copper which can produce beam hardening effect. The amount of beam hardening can be determined by a thickness of a modulation layer, provided that material and density of a modulation layer are unchanged. In order to evaluate the possibility of modulation layer based dual energy cone-beam CT, we analyze the beam hardening effect by the mean energies of the x-ray spectra for various thicknesses of modulation layers by Monte Carlo simulation. And the x-ray spectra acquired by Monte Carlo simulation are compared with x-ray spectra acquired by CdTe spectrometer experimentally.

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Materials and Methods

In this study, previously developed prototype kV cone-beam CT was modeled by MCNPX 2.7.0 code.[6] Source-to-detector, source-to-object, and object-to-detector distances were 90.0, 64.3, and 25.7 cm, respectively. Source energy spectrum was generated by SPEC78 which is a widely used x-ray spectrum generation program with tungsten target and two peak tube voltages as 80 and 120 kVp.[7] We assumed that a modulation layer was located at 20.0 cm in front of x-ray window (Fig. 1). The material and physical density of modulation layer were assumed as copper and 8.96 g/cm^3. The thicknesses of modulation layer were modeled as 0.3, 1.0, and 2.0 mm. The dimensions of height and width were 15.0×15.0 cm^2 in order to fully cover the x-ray window. We simulated CdTe detector at the position of an object, 64.3 cm apart from the x-ray window, and f8 tally and energy card with interval of 0.5 keV were used to acquire energy spectrum. The beam hardening effects were evaluated by comparing the mean energies of energy spectra. The mean energies of energy spectra acquired by Monte Carlo simulation were compared with that of measured energy spectra by Amptek XR-100T CdTe detector which has detection volume as 5.0×5.0×1.0 mm^3. In experimental setup, we used pin hole collimator and lead protector in order to prevent signal saturation (Fig. 2). Previously, the CdTe detector was calibrated with isotopes such as Na^{22}, Ba^{133}, Cs^{137}, Co^{60}, and Co^{57} which emit gamma rays from 14.4 keV to 1.3 MeV

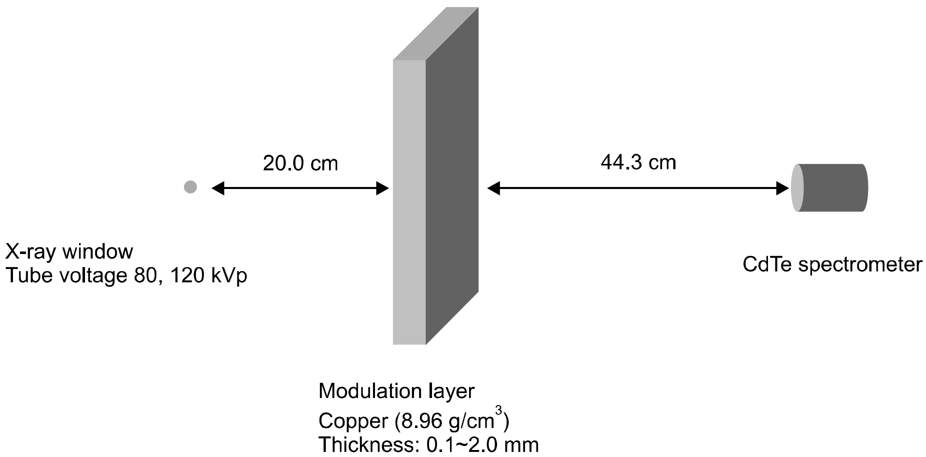


Fig. 1. Geometrical modeling of Monte Carlo simulation. Modulation layer and CdTe spectrometer are located at 20.0 cm and 64.3 cm distances from x-ray window, respectively.

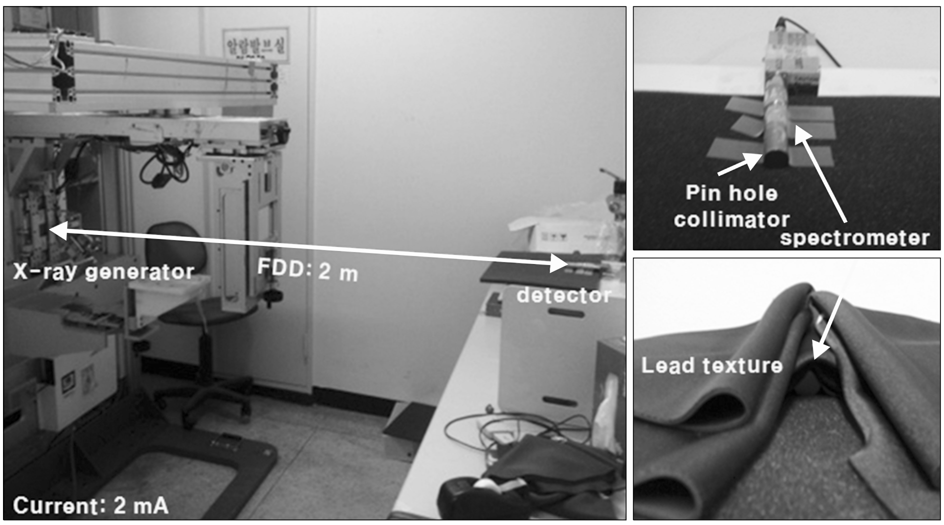


Fig. 2. Experimental setup for measuring the energy spectrum with CdTe XR-100T detector. Pin hole collimator and lead texture were used to prevent saturation. Pin hole collimator has narrow hole with 0.3 mm diameter.

(Fig. 3). Table 1 shows the energies of emitted gamma rays and their branching ratio of five isotopes, respectively.

Results

Fig. 4 shows the measured gamma-ray spectra of the five isotopes. We calibrated the XR-100T CdTe detector for the energy range from 14.4 keV to 1.3 MeV with these results. After the energy calibration, energy spectra were measured for five peak tube voltages as 50～100 kVp of our prototype cone-beam CT. The characteristic x-ray peaks of detector materials such as Cadmium and Telluride were shown in the energy spectra for 80 kVp or higher peak tube voltages (Fig. 5). The mean energies of the measured and simulated energy spectra for 80 kVp were 40 and 37.5 keV, respectively.

In the simulations, the energy spectra were acquired for two peak tube voltages such as 80 and 120 kVp with x-ray window blocked and unblocked x-ray window by modulation layer. For both peak tube voltages, beam hardening effects were well observed (Fig. 6a and b). The mean energies of energy spectra were 37.5 and 56.2 keV for 80 and 120 kVp with unblocked x-ray window. The mean energies of energy spectra were 53.5, 59.9, and 62.7 keV for 80 kVp, and 69.3, 78.3, and

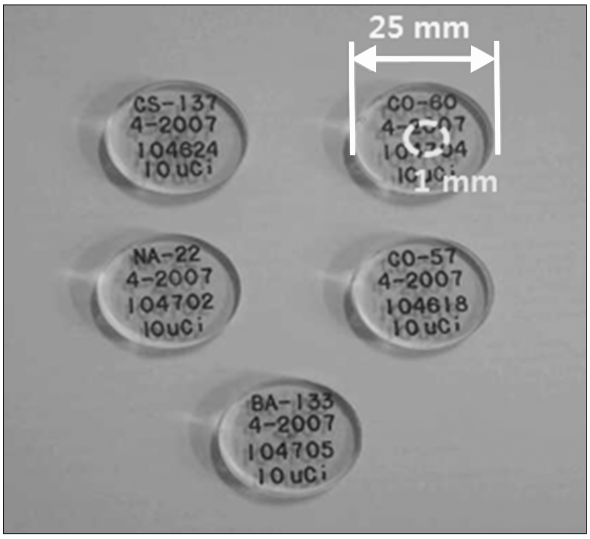
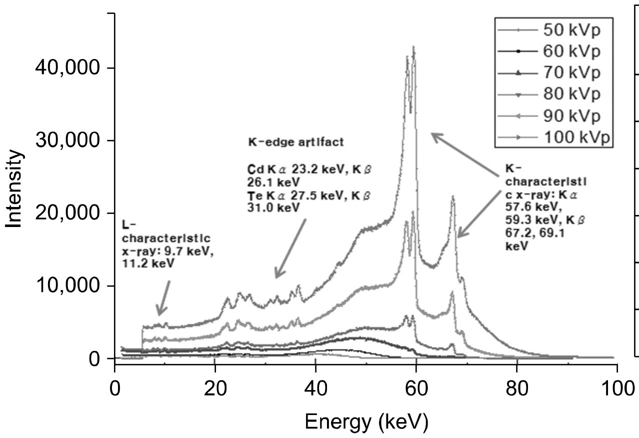


Fig. 3. Photography of five isotopes used to calibrate CdTe XR-100T detector. The diameter of isotope is 1.0 mm and is enveloped in 25.0 mm diameter plastic protector.

Table 1. The energies of emitted gamma-rays from the selected five isotopes.

Isotopes	Energy of emitted gamma-ray (branching ratio)
Na^{22}	1.275 MeV (100%)
	511 keV (181%)
Ba^{133}	81 keV (34%)
	276 keV (18%)
	303 keV (18%)
	356 keV (62%)
Cs^{137}	662 keV (85%)
	36 keV (1%)
	32 keV (6%)
Co^{60}	1.173 MeV (100%)
	1.332 MeV (100%)
Co^{57}	14.4119 keV (9.54%)
	122.0612 keV (85.6%)
	136.4730 keV (10.6%)



Peak tube voltage (kVp)	Mean energy (kVp)
50	27
60	32
70	36
80	40
90	45
100	48

Fig. 4. Five energy spectra for energy calibration of CdTe XR-100T detector with five isotopes such as Na^{22}, Ba^{133}, Cs^{137}, Co^{60}, and Co^{57}.

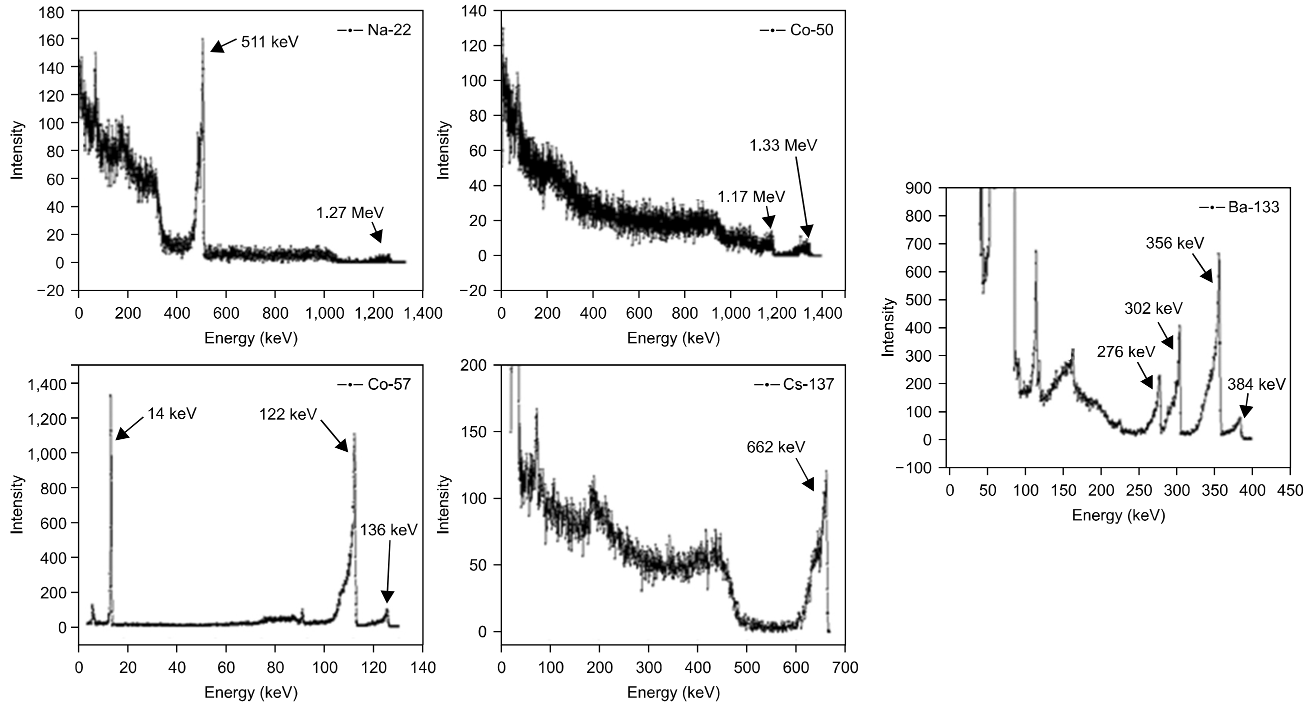


Fig. 5. Energy spectra acquired by CdTe XR-100T detector and their mean energy. The characteristic x-rays of detector materials, Cadmium and Telluride, are showed for peak tube voltage above 80 kVp.

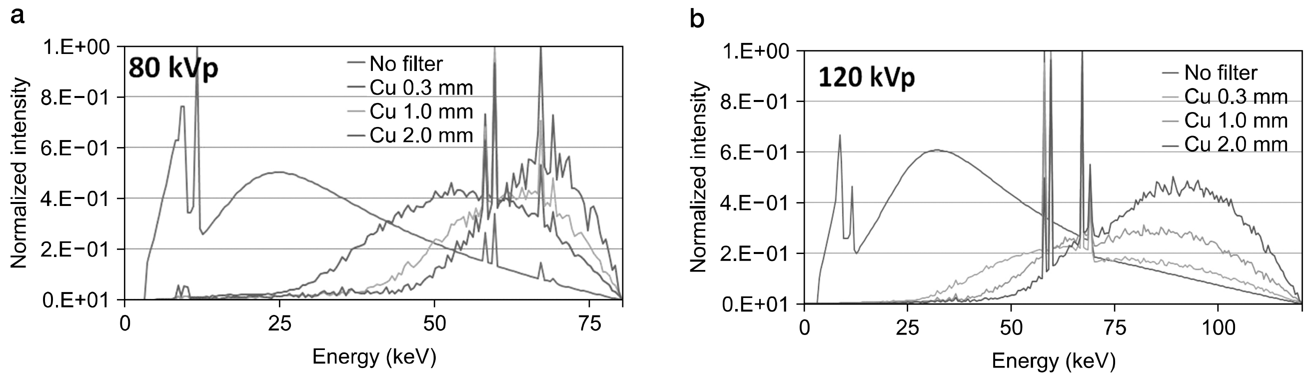


Fig. 6. Energy spectra acquired by Monte Carlo simulation without modulation filter and with modulation filters for (a) 80 kVp and (b) 120 kVp.

85.4 keV for 120 kVp with blocked x-ray window by the modulation layers of which thicknesses were 0.3, 0.5, and 2.0 mm, respectively.

Discussions

Several publications have handled the distinguishability of dual energy cone-beam CT between two materials with different atomic compositions. Liu et al. reported the method for distinguishing three materials by a mass conservation based three-material decomposition dual-energy CT algorithm.[8] The authors explained that different materials have different mass attenuation coefficients is the basic principle of dual-energy imaging. Hunemohr et al. have reported that the dual-energy CT can approve the accuracy of mass density prediction for 71 tissues such as adipose tissue, red marrow, and urine et al., therefore, dual-energy CT can improve the accuracy of the stopping power prediction.[9] Goodsitt et al. have reported the correlation between a phantom size and accuracy of mass density prediction in dual energy cone-beam CT. Their results showed that the root mean square of CT number of red marrow in bone spongiosa is larger than small phantom as 1.3∼1.5 times.[10]

In this study, the results of beam hardening effect with various thicknesses of modulation layers could be the basic data on the development of modulation layer based dual energy cone-beam CT. We will perform the next research about the quality of images acquired by modulation layer based dual energy cone-beam CT.

Conclusion

The modulation layer with 2.0 mm thickness can increase mean energies of energy spectra as 1.67 and 1.52 times than original mean energies for 80 and 120 kVp, respectively. Therefore, we realized that the modulation layer can generate virtual dual-energy x-ray source, one has the original peak tube voltage and the other has higher peak tube voltage than original one as 1.6 times.

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에너지 변조 필터로 구현한 이중 에너지 콘빔 CT의 에너지 스펙트럼 평가 연구

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이중 에너지 콘빔 CT는 원자번호가 다른 두 물질을 구분해낼 수 있다는 장점을 가진다. 이중 에너지 콘빔 CT를 구현하는 여러 가지 방법 중, 에너지 변조 필터(modulation layer)에 기반한 이중 에너지 콘빔 CT의 원리는 x-선 발생창의 절반을 구리와 같은 에너지 변조 필터로 차단하면, 차단되지 않은 곳에서는 원래의 관전압에 해당하는 x-선 스펙트럼이 발생하고 에너지 변조 필터로 가려진 부분에서는 저에너지 x-선이 감소된 x-선 스펙트럼이 발생하여 한 번의 스캔에서 두 가지 스펙트럼을 획득할 수 있다는 것이다. 우리는 에너지 변조 필터를 이용한 이중 에너지 콘빔 CT 구현의 가능성을 평가하기 위하여 다양한 두께의 에너지 변조 필터에 의해 생성되는 x-선 스펙트럼을 몬테칼로 전산모사를 이용하여 획득하였다. 전산모사 결과를 검증하기 위하여 동일한 콘빔 CT 시스템에서 CdTe 검출기를 이용하여 50∼100 kVp에 대하여 스펙트럼을 측정하였고, 80 kVp 관전압에 대하여 실험과 전산모사로 획득한 스펙트럼의 평균 에너지가 유사함을 확인하였다. 또한 에너지 변조 필터의 두께를 2.0 mm로 하였을 때 스펙트럼의 평균 에너지는 80과 120 kVp에 대하여 각각 1.67, 1.52배까지 증가함을 확인하였다. 따라서 에너지 변조 필터를 사용하면 하나의 x-선 발생장치를 이용하여 가상의 이중 에너지 선원을 구현할 수 있음을 확인하였다.

중심단어: 이중 에너지 콘빔 CT, 에너지 강화 효과, 에너지 변조 필터, 몬테칼로 전산모사