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Possible use of CdTe detectors in kVp monitoring of diagnostic x-ray tubes

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Abstract

It has been suggested that kVp of diagnostic X-ray devices (or maximal energy of x-ray photon spectra) should be monitored routinely; however a standardized noninvasive technique has yet to be developed and proposed. It is well known that the integral number of Compton scattered photons and the intensities of fluorescent x-ray lines registered after irradiation of some material by an x-ray beam are a function of the maximal beam energy. CdTe detectors have sufficient energy resolution to distinguish individual x-ray fluorescence lines and high efficiency for the photon energies in the diagnostic region. Our initial measurements have demonstrated that the different ratios of the integral number of Compton scattered photons and intensities of K and L fluorescent lines detected by CdTe detector are sensitive function of maximal photon energy and could be successfully applied for kVp monitoring.

Keywords

CdTe detector; x-ray spectroscopy; diagnostic x-rays; kVp monitoring

1. Introduction

In the diagnostic x-ray imaging the peak voltage of the x-ray tube (kVp) is one of the most important parameters. Small changes in the high voltage supply (the electron accelerating potential) can cause significant modification in the absorbed dose for routine diagnostic procedures. It has been shown [1] that the photon penetration ability due to small kVp variations can degrade the image contrast in mammography. It has been suggested [2] that the peak x-ray voltages should be routinely monitored. However a standardized technique for kVp has not been proposed. Different types of penetrameters [3,4] (kVp meters) are widely used in non-invasive measurements, but their readings depend upon several factors: the target material, type of filtration, the choice of high voltage waveform, etc. The direct measurement of x-ray spectra can be used to deduce the kVp. The value of the energy at which the end of the spectrum intersects the background is defined as the endpoint energy. The golden standard in photon spectroscopy HPGc detector was used in direct kVp determination [5] as well in indirect measurement by the detection of fluorescent lines [6]. However, the HPGc detector that requires cryogenic cooling is too expensive and not practical in clinical environments. Some

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possibilities of spectroscopy using small silicon photodiodes are presented in the literature [7–9] but the low efficiency at high energies seems to be the most important disadvantage, especially in Compton measurements. Several authors have applied CZT [10,11] and CdTe [12] to x-ray spectroscopy. Some complications have arisen when CZT and CdTe were exposed to a relatively high intensity of radiation in the x-ray beam. Detrapping current can cause limitations in response speed [13]. It reduces energy resolution and significantly shifts the energy calibration at high count rates [14]. X-ray spectra of diagnostic units can be reconstructed from spectra of Compton scattered photons [15,16].

Some alternative methods for the kVp finding, based on the x-ray fluorescence have been investigated several times. First attempts employing low resolution detectors [17,18] had limited success. Some authors [19] used high-resolution room-temperature silicon detector to show that the intensity of fluorescent K line of a target placed in the x-ray beam can be used for the precise and the absolute kVp determination. The recorded spectra of radiation emitted after exposure of some chosen target placed in the beam of a diagnostic x-ray machine contains three different components: the L fluorescent lines, Compton scattered radiation and the K fluorescent lines (if endpoint energy is high enough). Recently, some spectroscopy systems equipped with CdTe detectors have become commercially available. The CdTe detectors have the energy resolution comparable with Ge detectors, high intrinsic efficiency in the range of diagnostic energies, do not need cryogenic system and can be successfully used in clinical environments. In this paper, we would like to analyze how the intensities of K and L fluorescent lines as well as the intensity of Compton radiation can be utilized in the possible monitoring of the endpoint energy (kVp) of diagnostic beam.

Filtration of x-ray beams can significantly change the shape of spectra and have an effect on the intensity of fluorescent and scattered radiation. To get general indication as to how filtration can influence the final result, measurements were repeated using different thicknesses of Al layers located between x-ray tube and collimators.

2. Material and Methods

2.1 Experimental Setup

In the experiment the X-rays were generated by a non-stabilized 80 kVp x-ray tube, (available in our laboratory) with a tungsten target and an adjustable current of up to 1mA. The inherent filtration of the x-ray tube is equivalent to 1.8 mm Al. The scheme of experimental setup is presented in Figure 1. Two 2 mm diameter pin-hole collimators were designed to formulate a narrow beam and limit the exposed area of the target located 50 cm from the x-ray tube. The photon detector (AMPTEK XR-100T CdTe) consisted of relatively small ($3 \times 3 \times 1 \text{ mm}^3$) CdTe crystal and associated components were used. The detector was located 40 cm from the irradiated target and there were no additional collimation in the direction of detector. Scattered beams were measured at a variety of angles from 60° to 120° relatively to the direction of the incident x-ray beam. Diameter of the exposed area (checked by the light source located at the place of the x-ray tube) was less than 2 cm, including the penumbra. It means that uncertainty of the scattering angle, without additional collimation of the detector was about 2° . In possible clinical use of described setup, additional collimation of the detector should be introduced to define more accurately scattering angle, to shield detector from radiation scattered from other object, etc. Tube currents are usually much higher in diagnostic x-ray sources and additional collimation will be necessary to limit count rate and avoid distortion of Compton and fluorescent spectra. A 4096-channel ORTEC multi-channel analyzer (TRUMP-8K-32) was used to acquire spectra from the CdTe detection systems. The characteristic time of measurement was 60 seconds and tube current was not higher than $250 \mu\text{A}$. The applied high voltage ranged from 45 to 80 kV. Several materials covering a wide range of atomic numbers from Copper ($Z=29$) to lead ($Z=82$) were used as the medium for fluorescence and for

scattering. Electrolytic copper and pro-analysis metal coins were provided for experiment. To check the possible influence of filtration on intensities of scattered and fluorescent radiation, Al filters ranging from 129 mg/cm² (0.47 mm Al) to 849 mg/cm² (3.1 mm Al) were located between the x-ray tube and the first collimator.

2.2 Method

The integral count rate of Compton scattered radiation should be a sensitive function of endpoint energy of incident x-ray spectra. An increase of kVp elevates end-point energy of Compton distribution. For example, after 90° scattering of the incident X-ray beam that has maximal energy of the 40 kV, the end-point of Compton distribution will be 37.1 keV. If the kVp of incident radiation is 75 kV, the distribution of 90° Compton scattered photons will end at 65.4 keV. The amplitude of scattered radiation will be higher for higher kVp values, as can be seen from Figure 2. However, the integral intensity of Compton scattered radiation besides the endpoint energy of incident spectra depends also on a variety of experimental details: the type of scattering material, tube current, setup geometry, characteristics of detector etc. To make the measurement result less dependent on some of above mentioned factors, the integral intensities of Compton scattered radiation should be normalized by some quantity registered simultaneously with the same experimental setup. Intensities of fluorescent lines can be used for normalization. The material used as the medium for fluorescence and for scattering shouldn't have the binding energy of K electrons higher than the maximal energy of incident x-ray spectra.

If the ratio of the integral number of Compton scattered photons to integral number of K fluorescent photons (C/K ratio) is chosen to be the quantity for kVp monitoring, the scattering (and fluorescent) medium should be some light element. The C/K ratio will be the sensitive index of end-point energy only if the relative changes of intensity of fluorescent radiation in some range of incident x-ray beam's kVp are lower than the relative changes of integral intensity of Compton scattered radiation in the same range of kVp. It is well known that above the absorption edge, the probability of photo-effect varies roughly as $E^{-7/2}$. At higher energies, the photo-effect cross section can be described by E^{-1} function. For example, the photo-effect cross section for copper in an energy interval between 15 keV and 20 keV changes for a factor 2.2, but difference between the photo-effect cross sections in the energy interval from 50 keV to 55 keV is just 25%. If the end-point energy of an x-ray beam is several times higher than the K-edge of irradiated material, changes in kVp will affect the high energy part of the x-ray spectra. Changes of the high energy tail of the x-ray spectra should not be accompanied by prominent changes of the K fluorescent line intensity. Figure 3 shows relative changes of intensities of the integral Compton scattered radiation and intensity of Cu K fluorescent lines of end-point energy. It can be seen that relative change of intensity of K fluorescent line is linear (simple non weighted fit gives $r = 0.9994$). Relative changes of the integral intensity of Compton radiation can be described by simple power function $a \cdot E^{3.5}$. If some heavy element is used as a scattering medium and source of the fluorescence radiation, the intensity of L fluorescent lines should normalize the integral intensity of Compton scattered radiation.

It is referred [6,17] that the intensity of K fluorescent lines of heavy elements is very dependent on the high voltage supply of an x-ray tube. The intensities of fluorescent lines of heavy elements having K electron energies close to the end-point energy of the incident x-ray beam can be used to get a sensitive index for kVp monitoring. Considering that both K and L fluorescent lines of some heavy elements appear in the spectra, the ratio of intensities of these lines (K/L ratio) recorded simultaneously can be used as a sensitive index of kVp. This ratio, as well as the ratio of intensities of Compton scattered and low Z fluorescent K radiation is independent on several experimental parameters.

Attenuation properties of Cd and Te defined the constant value of intrinsic efficiency of the CdTe detector in the relatively broad energy region between 8 keV and 65 keV. However, the influence of the amplifier Rise Time Discriminator circuit can reduce the detector intrinsic efficiency. The relative detection efficiency of CdTe detector was estimated using ^{133}Ba . Integral intensities of three unresolved doublets (30.62 keV and 30.97 keV; 34.97 keV and 36.00 keV; 79.61 keV and 80.99 keV) as well as intensity of single 53.15 keV gamma line were used in calculations. It was obtained that relative efficiency is almost constant in the energy region between 30 keV and 53 keV. Relative efficiency at 53.15 keV is just about 5% lower than relative efficiency measured in the 30 keV energy region. However, relative efficiency at 80 keV is about 2.5 times lower than relative efficiency at 30 keV. It means that if some element having K-edge higher than 50 keV serves as the source of fluorescent radiation, stripping process should be applied to correct the effects of detector efficiency changes. In this preliminary study was assumed that relative efficiency of CdTe detector is constant in energy region between Cu and Hf K fluorescent lines. Adjustments of the measured spectra for the escape peaks of CdTe detector were not done in this preliminary study.

Two point calibrations of the energy spectra were made using 14.41 keV and 122.06 keV gamma lines from a ^{57}Co radionuclide source. If some heavy element is employed as a target, K and L fluorescent lines can be used for energy calibration.

Considering that the available x-ray tube was not stabilized or calibrated, another CdTe detector was placed in the beam, about 200 cm behind the irradiated target (detector 2 at a Figure 1). The target was periodically mowed and actual kVp was measured by the direct measurement of x-ray spectra to calibrate HV readout of the x-ray equipment. The voltage equivalent energy at which the high-energy end of the spectrum (approximated by straight line for the last few keV) intersects the background, assumed to be linear, is defined as the end-point energy (or kVp). To prevent possible distortion or energy shift of the spectra due to high count rate, Al attenuator was placed in the front of the detector. Through an appropriate choice of measurement time an uncertainty in the estimated endpoint energy of about 3% was obtained.

3. Results and Discussion

The spectra recorded by the use of a CdTe detector and a copper target (Figure 2) have two distinct components: the Cu fluorescent lines and the Compton continual distribution. The total intensity of K triplet (8.028 keV $K_{\alpha 2}$; 8.045 keV $K_{\alpha 1}$ and 8.905 keV $K_{\beta 1}$) was determined by the proper subtraction of Compton continuum in the energy region of fluorescent lines. A linear interpolation between continuum values on either side of the observed peaks was used. The intensity of Compton scattered radiation was determined by integration starting from 12 keV to the end of continual distribution. In the described geometry, the maximal integral count rate was about 3000 counts per second and maximal dead time was less than 6%. It allowed us to determine integral intensity of fluorescent and Compton radiation with the statistical uncertainty lower than 1% in most of the measurements. Relative intensities of the Compton scattered and K fluorescent radiation emitted from the Cu target irradiated by the x-ray beam with kVp ranging from 40 kV to 79 kV are presented on Figure 3. All points presented in Figures 3 to 9 are connected by line, only to guide the eyes. No fitting procedure was done.

Relative changes of intensity of radiation scattered in copper (normalized by K fluorescent lines) for three different filtrations are presented on Figure 4. It can be seen that the sensitivity of Compton to fluorescence technique increases with the increase of filtration. The ratio of integral Compton and copper K fluorescence line varies by a factor 3.25 in the kVp region between 40 kV and 80 kV when additional filtration (except inherent one) is not applied. In the same interval of x-ray tube kV supply, the copper C/K ratio changes for a factor 5.25 when additionally 590 mg/cm^2 (2.2 mm) of Al is added.

A similar procedure was repeated using lead as scattering and fluorescent medium. The integral intensity of Compton scattered radiation was normalized by the integral intensity of L triplet (L_{α} -10.54 keV; L_{β} -12.07 keV and L_{γ} -14.92 keV). The Compton and fluorescent radiations from lead are several times more intensive than the corresponding radiation emitted from the copper target. However, the relative change of Compton to fluorescent ratio measured using lead target is up to 50% lower than the C/K ratio measured using a Cu scattering medium in the observed region of kVp. Figure 5 shows the comparison between relative changes of Compton to fluorescent ratio measured using copper and lead. The presented data were collected using additional 1.55 mm (419 mg/cm²) of Al filter. Similar results were obtained using different thicknesses of Al filtration.

The Compton to fluorescent ratio was measured at several scattering angles between 60° and 120° relative to the direction of incoming photons. The intensity of radiation, backscattered at 120° is much lower than the intensity of a forward scatter radiation (scattered at 60°), as it can be expected. However, the relative changes of Compton to fluorescent ratio are relatively similar for all scattering angles between 60° and 120°. Figure 6 shows the relative Compton to fluorescent ratio of the Cu target for three different scattering angles measured with 1.55 mm thick Al filter added.

Several different heavy elements were used in the experiment. In this paper results obtained by the measurement of Compton scattered and fluorescent radiation after an exposition of Hf target will be presented. The intensity of K fluorescent line was obtained as an integral intensity of $K_{\alpha 1}$ (54.6 keV) and $K_{\alpha 2}$ (55.7 keV) doublet. The intensity of L fluorescent line means integral of L triplet (L_{α} -7.89 keV, L_{β} -9.08 keV and L_{γ} -10.58 keV). The intensities of fluorescent lines were determined by a standard subtraction of the background Compton continuum under the lines. The absolute values of hafnium K/L ratio in the kVp interval ranging from 67.5 kV to 79 kV are presented in Figure 7. The K radiation fluorescence is relatively weak at 67.5 kV and the intensity of K_{α} doublet is determined with 30% uncertainty (at 1 σ confidence level). It was a reason why the normalization by the measured K/L ratio obtained using the lowest voltage was avoided in this case. The intensity of K fluorescence lines increases very fast with the increase of kVp and K/L ratio at 70 kV was determined with the experimental uncertainty of 5%. It should be emphasized that the relative difference of K/L ratio between the two selected values of kVp shows an increasing trend with the increase of filtration. The Hafnium K/L ratio at 80 kV is 8.67 times higher than the corresponding ratio measured at 70 kV in absence of an additional filtration (except the inherent one). At the highest filtration used in the measurement (849 mg/cm² Al), the K/L ratio at 80 kV is 10.5 times higher than the K/L ratio obtained at 70 kV.

Systematic measurements with several Al filters of different thicknesses (ranging from 0 mg/cm² to 849 mg/cm²) at some fixed value of kVp were done. The obtained values of Compton to K fluorescence ratio for Cu target are presented in Figure 8 (scattering angle was 90°). It can be seen that the C/K ratio slowly increases with increase of filtration. For the highest value of filtration (849 mg/cm² Al) used in this experiment, the C/K ratio is up to 60% higher than the C/K ratio obtained in the absence of the additional filtration, for all used values of kVp. A similar trend was obtained for the ratio of intensities of K and L fluorescent lines. For example, the hafnium K/L value measured with 849 mg/cm² Al filtration was about 55% higher than the K/L value obtained without additional filtration. The lowest dependence on filtration was observed for the ratio of intensities of Hf fluorescent K_{α} lines and the intensity of Compton scattered radiation (K/C ratio). In this case the continual Compton distribution of scattered radiation in the energy region between L and K fluorescent lines was used in calculation. Figure 9 shows the dependence of intensity of Hf fluorescent K_{α} line to Compton ratio for two different values of filtration. The difference between the hafnium K/C ratio measured without additional filtration and the K/C ratio obtained after filtration through 849 mg/cm² was less than 30%.

4. Conclusion

Recently developed CdTe detectors can be successfully applied in the measurement of scattered and fluorescent radiation. Considering that the intensities of both components are significantly lower than the primary x-ray beam intensity, problems appearing at the higher count rates can be avoided. In reported measurements relatively low tube currents and long exposure times were used. In practice, most of the diagnostic devices operate at higher currents. In this case, the optimal count rate can be achieved by the proper choice of collimation and geometry.

Recorded spectra contain fluorescent lines superposed on a continual distribution of Compton scattered radiation. The intensities of three components (K and L fluorescent lines, as well as Compton continual distribution) of the recorded spectra are dependent on high voltage supply of the x-ray tube and can be used as sensitive index of kVp. Considering that a proper choice of irradiated target can give at least two of already mentioned three components of the measured spectra, the ratio of their intensities can be calculated. This ratio depends on the kVp, but do not depend on several parameters (tube current, geometry, some detector properties etc.).

It is shown that the ratio of the intensities of Compton scattered radiation and low-energy K fluorescent line of some medium heavy element (as copper, for example) changes for a factor 5 in the range of applied tube high voltages between 40 kV and 80 kV. Sensitivity of the method is similar for different scattering angles, between 60° and 120°.

If some heavy elements (having binding energies of K electrons slightly lower than the endpoint energy of incident spectra) are irradiated, both K and L fluorescent lines can be seen in the recorded spectra. The ratio of intensities of K and L fluorescent lines is a very sensitive function of kVp. The preliminary measurements showed that the K/L ratio of Hf target is one order of magnitude higher at 80 kV than at 70 kV. A proper choice of fluorescent material can make the K/L technique feasible in the broad range of x-ray tube kVp used in the diagnostic practice.

The intensity of Compton scattering and fluorescence depends on filtration of the beam. This can be explained by the fact that the intensities of low-energy fluorescent lines (L or K lines of low Z materials) are very dependent on changes of x-ray spectra accompanied by filtration. The high energy part of Compton scattered radiation or the K fluorescent lines having energy close to the end of x-ray spectra do not depend on filtration as low-energy fluorescent lines. The data presented on Figures 8 and 9 can point to the conclusion that use of thick Al filters can make some ratios independent on filtration. There is some room for developing of the described method by the optimal selection of data recorded in the spectra of scattered and fluorescent radiation, geometry, choice of scattering medium, better determination of detection efficiency, etc. In further research the Compton scattered and fluorescent radiation (and their ratios) should be analyzed for a broad variety of diagnostic x-ray tubes having different end-point energies and filtration.

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References

1. Law J, Faulkner K, Smith S. Measurement of x-ray tube potential in the mammographic region. *Phys Med Biol* 1989;34:717–725. [PubMed: 2740439]
2. Quality Control in Diagnostic Radiology, Diagnostic x-ray Imaging Committee Task Group #12. AAPM Report 2002;74

3. Jacobson AF, Cameron JR, Siedband MP, Wagner J. Test cassette for measuring peak tube potential of diagnostic x-ray machines. *Medical Physics* 1975;3:19–25.
4. Netto TG, Cameron JR. An inexpensive kVp penetrometer. *Medical Physics* 1985;12:259–260. [PubMed: 4000090]
5. Giarratano JC, Waggener RG, Hevezi JM, Shalek RJ. Comparison of voltage-divider, modified Ardran-Crooks cassette, and Ge(Li) spectrometer methods to determine the peak kilovoltage (kVp0) of diagnostic x-ray units. *Medical Physics* 1976;3:142–147. [PubMed: 934032]
6. Rauch PL, Channey EL, Carson PL, Hendee WR. Absolute kilovoltage calibration of a diagnostic x-ray generator. *Medical Physics* 1975;2:1–4. [PubMed: 1128454]
7. Aoki K, Koyama M. Measurement of diagnostic x-ray spectra using a silicon photodiode. *Med Phys* 1989;16:529–536. [PubMed: 2770626]
8. Silva MC, Herdade SB, Lammoglia P, Costa PR, Terini RA. Determination of the voltage applied to x-ray tubes from the bremsstrahlung spectrum obtained with silicon PIN photodiode. *Med Phys* 2000;27:2617–2623. [PubMed: 11128315]
9. Kunzel R, Herdade SB, Terini RA, Costa PR. X-ray spectroscopy in mammography with a silicon PIN photodiode with application to the measurement of tube voltage. *Med Phys* 2004;31:2996–3003. [PubMed: 15587652]
10. Matsumoto M, Yamamoto A, Honda I, Taniguchi A, Kanamori H. Direct measurement of mammographic x-ray spectra using a CdZnTe detector. *Med Phys* 2000;27:1490–1502. [PubMed: 10947252]
11. Miyajima S, Imagawa K, Matsumoto M. CdZnTe detector in diagnostic x-ray spectroscopy. *Med Phys* 2002;29:1421–1429. [PubMed: 12148722]
12. Miyajima S. Thin CdTe detector in diagnostic x-ray spectroscopy. *Med Phys* 2003;30:771–777. [PubMed: 12772983]
13. Jahnke A, Matz R. Signal formation and decay in CdTe x-ray detector under intense irradiation. *Med Phys* 1999;26:38–48. [PubMed: 9949396]
14. Krmar M, Shukla S, Ganezer KS. Some aspects involving the use of CdTe for finding end-point energies in diagnostic radiology. *Applied Radiation and Isotopes* 2006;64:584–587. [PubMed: 16376090]
15. Baldazzi G, Bernardi T, Fernandez JE, Ferrari P, Rossi PL, Testoni G, Zannoli R. X-rays spectroscopy with a portable Compton selection chamber: detector design and results. *Nuclear Instruments and Methods in Physics Research B* 2004;213:223–226.
16. Matscheko G, Ribberfors R. A Compton scattering spectrometer for determining x-ray photon energy spectra. *Nuclear Instruments and Methods in Physics Research B* 1987;255:326–329.
17. Greening JR. The measurement by ionization methods of the peak kilovoltage across x-ray tubes. *Br J Appl Phys* 1955;6:73–79.
18. Bloch P, Hale J. Calibration of potential of x-ray generators in the diagnostic energy region. *Phys Med Biol* 1966;11:577–589. [PubMed: 5969858]
19. Anderson DW, Moore GJ, Lester PD. Absolute kVp calibration using characteristic x-ray yields. *Med Phys* 1986;13:663–666. [PubMed: 3784993]

Figure 1.

Experimental setup. Tube – target and target detector distance were 50 cm and 40 cm simultaneously. Collimator holes have 2 mm diameter. The 3mm thick lead plates were used for collimators.

Figure 2.

Comparison of two spectra recorded at 90° . The high voltage supply of the tube was 40 kV and 75 kV. Tube current and measurement time were the same in both cases. The copper target was used.

Figure 3. Ratio of intensities of the Compton scattered and K fluorescent radiation emitted from the Cu target irradiated by the x-ray beam with kVp ranging from 40 kV to 79 kV.

Figure 4.

Changes of the ratio of intensity of Compton scattered radiation and Cu K fluorescent line for several different filtration. The “0 mg/cm²” means that the additional filters were not applied. This beam was tailored just by the 1.8 mm of Al of inherent filtration.

Figure 5.

Relative ratio of intensities of the Compton scattered and fluorescent radiation measured for the Cu and Pb targets. When the Cu target was irradiated K fluorescent lines were used in calculation. In the case when Pb was exposed to the x-ray beam, intensities of the L fluorescent lines were measured and used in calculation.

Figure 6. Ratio of intensities of Compton scattered and fluorescent radiation of Cu for some different scattering angles. Data were collected using 1.55 mm thick Al filter.

Figure 7.
Ratio of intensities of K_{α} and L fluorescent lines of Hf as a function of kVp of the x-ray tube.

Figure 8.

Ratio of the intensities of Compton scattered radiation and K fluorescent line of the Cu target as a function of the beam filtration for the several different high voltages supplied to the x-ray tube. Thicknesses of additional Al layers are presented in Figure. “0 mg/cm” means just the inherent filtration.

Figure 9.

The ratio of the intensities of the K_{α} fluorescent lines of Hf and Compton scattered radiation as a function of filter thicknesses for two different high voltage of the x-ray tube.