MODIFIED POLYENERGETIC X-RAY SPECTRA FOR DUAL ENERGY METHOD

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Abstract. *The aim of the present study was the optimization of polyenergetic x-ray spectra for Dual energy imaging. The latter was accomplished by using various combinations of filter thicknesses and kVp. X-ray spectra were optimized by using double track x-ray tubes equipped with Molybdenum (Mo) and Rhodium (Rh), Mo and Tungsten (W), Rh and W, and a W or Rh anode combined with various K-edge filters and combinations. Filtering of energy spectra was implemented by determining the optimum combination and thicknesses of the lanthanides filters. The filtered spectra were normalized at standard exposure conditions. Best performance characteristics were obtained from the combination of Rh anode spectrum at 25kVp filtered with 100 μm Rh for low energy, and W anode spectrum at 50Vp filtered with 400 μm Ce for mammography, with mean energy values 19.57 and 30.10KeV respectively. For bone densitometry, best results were obtained from a W anode filtered spectrum at 110KVp with 900 μm Ce and mean energy values 37.78 and 85.56KeV for low and high energy respectively.*

1 INTRODUCTION

Simulation software's for generating filtered realistic polyenergetic x-ray are important components for dual energy imaging. The use of dual-energy methods has been investigated for several x-ray imaging and non-imaging procedures, including computed tomography, chest radiography, mammography and bone densitometry, respectively. Dual energy imaging involves the acquisition of two images by using x-rays of two different energies to exploit the difference in the energy dependence of x-ray attenuation between different materials [1].

The photon spectrum from a conventional x-ray tube consists of a broadband of energies. Although it is possible to use detectors with very narrow energy resolution, e.g., high-purity germanium, to resolve the broadband spectrum into low- and high- energy components, the more common approach is to shape the spectrum emitted from the source into two relatively narrow energy bands. This can be accomplished in three ways: K-edge filtering, kV switching or the combination of both. The output from the x-ray tube is filtered by a material having a k-shell absorption edge near the midpoint of the energy spectrum. Selective attenuation of photons just above the absorption edge creates a transmitted spectrum consisting of two relatively narrow bands. Only a single exposure is required with K-edge filtering because both energies are present simultaneously in the radiation beam. Energy discriminating detectors are acquired to separate the photon energies. Dual kV techniques employ two sequential measurements at different kilovoltages, typical with different beam filters mechanically moved into and out of the beam between exposures. Dual kV techniques require two separate exposures. However, no energy discrimination is required in the detector. The added filtration selectively removes lower energy photons from the high kV beam and also provides similar beam intensities at the detector, which otherwise would be much greater for the high kV beam [2,3]. By properly combining the low- and high-energies, the contrast between any two materials may be cancelled or reduced to enhance visualization in imaging procedures [4].

In recent years, several studies and simulation works have been carried out in order to investigate the factors that affect the choice of x-ray spectra for mammography. *Dance et al* in their Monte Carlo study concluded that in digital mammography the standard Mo/Mo combination is only superior for 2 cm breasts, while for all other breast thicknesses and glandularities, each of the alternative anode/ filter combinations (Mo/Rh, W/Rh, Rh/Rhand Rh/Al) can offer lower dose. In particular for breast thicknesses of 4 cm - 6 cm, W/Rh is recommended [5].

In a previous work, *Andre et al* developed a parametric model for digital mammography to evaluate optimization of x-ray spectra for a particular sensor. The model calculates spectra and average glandular doses (AGD) for combinations of W target, beam filters (Al, Sn, Rh, Mo and Ag), kVp, breast type and thicknesses. Based on their results, the authors suggest the use of Mo filter for 30 mm thick breast, Ag filter for 45 mm, Sn filter for 60 mm, and Al filter for 75 mm thick breast [6]. *Fahrig and Yaffe* in their simulation study demonstrated that using a digital detector based on Gd_2O_2S scintillator, a W target is preferable to a Mo target for the detection of infiltrating calcifications [7, 8]. In the work of *Flynn*, the radiographic process for a digital (amorphous Selenium) mammography system was modeled. The optimal contrast-to-noise ratio (CNR) relative to dose was determined for several target/filter combinations, for a wide range of kVp values, and for varying breast thicknesses. The target/filter combinations included: Mo/Mo, Mo/Rh, Rh/Rh, W/Al, W/Mo, W/Ag and W/Sn. Results show that when breast thickness increased, the use of a W target with a Sn filter resulted in a 34% improvement in CNR for the same dose to the breast when compared to the use of a Mo target with a Mo filter[9]. *Bernhardt et al* in their recent work found that for an amorphous selenium detector, the W/Rh combination is the best choice for all the breast thickness and composition and for the detection of both microcalcifications and tumors. Given these results and other similar published results, manufacturers have introduced mammography units with different anode/filter combinations such as Mo/Rh, Rh/Rh, W/Rh and W/Ag [10].

As for bone densitometry studies, a dual kV technique suggested by *Rutt*, in which a Holmium (Ho) K-edge filter is added for the low kV beam. The Holmium filter narrows the low kV spectrum, resulting in greater energy difference between the two spectra as well as decrease beam-hardening effects, due to narrowing of the low-energy spectrum. The high kV beam is filtered with 9.8 mm of copper (Cu) to provide similar transmitted beam intensities at the detector [11]. Yet another approach, suggested by *Gustaffson et al.*, is to use k-edge filters in both high and low kV beams to narrow both the low and high kV spectra [12].

The purpose of this study is to present the results of computer simulations analyzing the performance characteristics of various anode/filter combinations. Emphasis was placed on optimizing the K-edge filter technique in both mammography and bone densitometry.

2 MATERIALS AND METHODS

2.1 Software filtering

To determine the effect of varying filter thicknesses and kVp a computer program was developed. The program simulated filtered spectra with a variety of filter thicknesses and tube operating potentials. Unfiltered spectra were obtained from Boone *et al*. (1997 Med. Phys. **24** 1863-73) for Tungsten (W), Molybdenum (Mo) and Rhodium (Rh) anodes. Simulations provided values for the following quality parameters [13]: (i) mean energy, (ii) Full Width at Half Maximum (FWHM) and (iii) total counts. In order to determine the filtered spectra the exponential equation was used:

$$I(E) = I_o(E) * e^{-\frac{\mu}{\rho}(E)\rho t} \quad (1)$$

where I_o is the photon fluence per unit energy E incident on the surface of the filter, I is the transmitted fluence per unit energy E, μ/ρ is the mass energy attenuation coefficient of the material of filter at energy E, ρ is the density of the material and t is the thickness of the filter. Mass attenuation coefficients for filter materials were calculated from tabulated data on attenuation coefficients [14].

Extra procedure for the normalization of the filtered spectrum at standard exposure conditions was also included. Specifically the spectrum was normalized in terms of air KERMA at the entrance of the patient for 6 mGy entrance dose. The normalization is applied on the filtered spectrum according to following equation [15]:

$$K_a = \sum_{Emin}^{Emax} 1.83 * 10^{-6} * \Phi_0(E) * E * \left(\frac{\mu_{en}}{\rho}(E)\right)_{air} \quad (2)$$

where $\Phi_0(E)$ is the measured x-ray spectrum value (photons/mm^2) at energy E. $(\mu_{en}(E)/\rho)_{air}$ is the x ray mass energy absorption coefficient of air at energy E obtained from the literature [16].

2.2 Mammographic spectra

The gold standard source for mammographic examination is the molybdenum anode tube with a 0.03 mm molybdenum (Mo) filter. This source seems to be the best compromise among energy band width and the technological limits of generators and x-ray tubes in order to obtain high image quality and low-dose mammography for breasts of moderate transmission [17].

In this study, double track x-ray tubes equipped with Mo and rhodium (Rh), Mo and tungsten (W), Rh and W, and a W or Rh anode combined with various K-edge filters and combinations of these were simulated. All these new anode combinations result in harder beam qualities (i.e., higher mean photon energies) than the beam qualities with Mo-Mo tubes. The dual energy method was adapted to polyenergetic energy spectra. Filtering of energy spectra was implemented by determining the optimum combination and thickness of these filters. Also an inherent filtration of 2 mm Beryllium (Be) window was used in order to obtain the spectra of all anodes. The normalization of the filtered spectra at standard exposure conditions was implemented in terms of x-ray air KERMA at the entrance of the patient for 6 mGy total exposure (low- and high- energy exposure 4 mGy and 2 mGy respectively) [18].

2.2.1 Mo and W anode spectra

Four separate x-ray tube operating voltages of Molybdenum anode, from 25 to 40 KVp, in 5 KVp increments were investigated in order to obtain the low energy spectrum and 50 KVp of Tungsten anode for the high energy spectrum respectively. Molybdenum filtered spectra were acquired using three different filter materials (Molybdenum, Zirconium and Niobium) with thicknesses between 15 and 90 μm. Tungsten filtered spectra were acquired using four lanthanide filters (Ce, Nd, Sm, Eu), copper (Cu) and cadmium (Cd) with thicknesses from 130 to 600 μm.

2.2.2 Rh and W anode spectra

Similarly, two x-ray beams were produced from Rhodium and Tungsten anode tubes at 25, 30, 35, 40 KVp and 50 kVp respectively. Rhodium filtered spectra were acquired using three different filter materials (Rhodium, Ruthenium, and Aluminum) with thicknesses between 50 to 900 μm. Tungsten filtered spectra were acquired using four lanthanide filters (Ce, Nd, Sm, Eu), copper (Cu) and cadmium (Cd) with thicknesses from 130 to 600 μm.

2.2.3 Rh anode spectra

In the first case the x-ray tube produced two x-ray beams at 25 and 40 kVp and in the second 28 and 40 kVp respectively. In both cases rhodium (Rh), ruthenium (Ru), aluminum (Al) and combinations of these were selected. The filter thicknesses were between 50 to 900 μm.

2.2.4 W anode spectra

The x-ray tube produced two x-ray beams at 30 and 50kVp. Four lanthanide filters (Ce, Nd, Sm, Eu), silver (Ag), copper (Cu), cadmium (Cd), rhodium (Rh), molybdenum (Mo), palladium (Pd) and combinations of these were selected on the basis of their K-edge. The filter thicknesses were between 100 to 600 μm. Added aluminum filtration (1mm) was applied for further beam hardening in 30 kVp spectrum.

2.2.5 Mo and Rh anode spectra

The Mo and Rh filtered spectra were simulated at 25, 30, 35, 40 KVp and 50kVp respectively. For the Molybdenum anode, three filters were used (Molybdenum, Zirconium and Niobium) with thicknesses from 15 to 90 μm. Rhodium filtered spectra were acquired using three different filters (Rhodium, Ruthenium, and Aluminum) with thicknesses from 80 to 900 μm.

2.3 Bone densitometry spectra

The dual energy method was adapted to polyenergetic energy spectra. Filtering of energy spectra was implemented by determining the optimum combination and thickness of the lanthanides filters used in this study. The filter thicknesses were from 200 to 950 μm and the filter combinations that were examined used known values of mass attenuation coefficients (μ / ρ) for the Ce, Nd, Sm, Eu, Gd, Er, Yb, and Ho elements. The spectra from a Tungsten (W) anode with inherent filtration 2.5 mm Al was used [19]. The normalization of the filtered spectra at standard exposure conditions was implemented in terms of x-ray air KERMA at the entrance of the patient for 6 mGy.

Two methods were applied for spectra modification. In the first method, single exposure with K-edge filtering was applied. X-ray tube voltages of 110, 115 and 120 KVp with proper filtration were examined. Eight lanthanide filters (Ce, Nd, Sm, Eu, Gd, Er, Yb, and Ho) were selected on the basis of their K-edge in the range from 40keV to 62keV [20]. In the second method, the x-ray tube produced two x-ray beams at 60 and 120kVp. The double exposure technique provides a sufficient photon energy range both above and below K-edge by combining voltage switching and K-edge filtering technique.

3 RESULTS AND DISCUSSION

Simulations results concerning the evaluation of K-edge filtered W, Mo, and Rh anode spectra are shown below. Indicative examples of filter performance in mammographic and bone densitometry spectra are given in Tables I and II respectively. Mean energy values for both cases are in the range of accepted values reported in previous studies [21, 22].

Anode	**kVp**	**Filter**		**Total Counts ($*10^5$)**		**Mean Energy**		**FWHM (keV)**	
		LE	***HE***	***LE***	***HE***	***LE***	***HE***	***LE***	***HE***
Mo_Rh	25_40	Mo/Zr(30/90 μm)	Rh/Al(100/900 μm)	2	1.74	16.57	20.75	1.2	5
Rh_W	25_50	Rh(100 μm)	Ce(400 μm)	1.06	6.24	19.57	35.10	2.75	7
W	50	Cd(130 μm)	Cu(400 μm)	11.9	5.67	29.35	39.08	4.5	12.5
Mo_W	30_50	Mo/Al(30/900 μm)	Nd(500 μm)	2.24	3.65	17.64	37.78	9.5	8

Table I: Mammographic filter performance.

Anode	**kVp**	**Filter**		**Total Counts ($*10^5$)**		**Mean Energy**		**FWHM (keV)**	
		LE	***HE***	***LE***	***HE***	***LE***	***HE***	***LE***	***HE***
W	110	Ce(900 μm)		5.1		37.78	85.56	2	27
W	115	Gd/Sm(400/350 μm)		5.33		42.97	90.19	3	28
W	120	Nd(700 μm)		10.6		39.92	89.44	3	34
W_W	60_120	Sm(400 μm)	Nd/Sm (550/800 μm)	13.7	1.36	39.97	98.76	6	24

Table II: Bone densitometry filters performance.

For a thinner breast the optimal energy is almost equal to the Mo Kα line (17.4 keV) thus, a suppression of the Mo Kβ line (19.6 keV) from the molybdenum anode spectrum may be desirable [17]. The suppression of the Kβ line from the x-ray spectrum of a molybdenum anode tube may be achieved by using a niobium filter (Z=41, K-edge at 19 keV). In Figure 1, the spectrum of a system with Mo Kβ line suppression, based on a double K-edge filter (Nb/Mo) is compared with that of a niobium-filtered spectrum. This sandwich filter absorbs the Mo Kβ line more than does the 150 μm Nb filter. Since the power of the x-ray tube limits the thickness of the filter, an appropriate Nb thickness has to be chosen. To avoid overloading of the tube [2], a reasonable compromise is represented by a combination of Nb/Mo filters of thicknesses 150 and 200 μm, respectively.

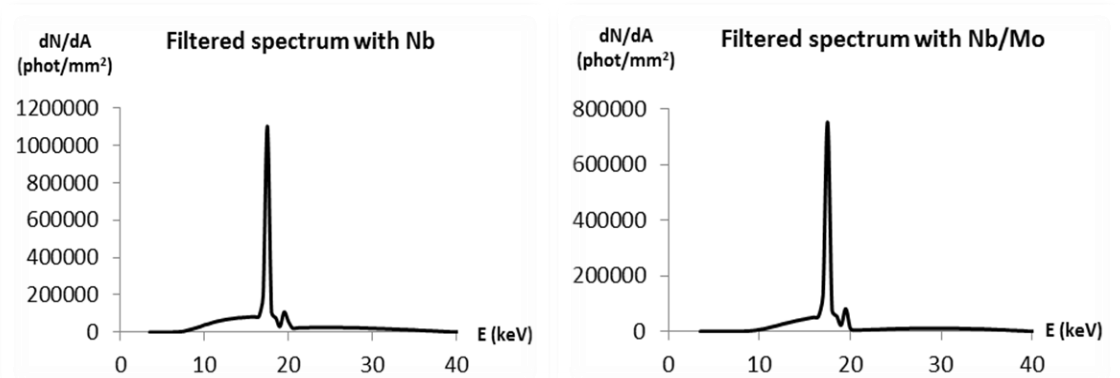


Figure 1. Mo anode spectra at 40 kVp with added filtration of 15 μm Nb and 15/20 μm Nb/Mo.

Figure 2 shows a Rhodium anode spectrum filtered with Ruthenium/Rhodium (Ru/Rh) at 25kVp. The combination of Ru/Rh removed the low-energy photons and resulted in beam hardening which can be confirmed by the mean energy values (from 18.90 keV for Rh to 19.40 keV for Ru/Rh).

Figure 3 shows double exposure W anode spectra at 30 and 50kVp filtered with Pd and Cu, respectively. Among different filters applied to the 30kVp W spectrum, Pd filter was the one that gave quasi-monochromatic spectrum (FWHM=5 keV). These filtered spectra had smaller overlap compared with others obtained with the same tube potentials.

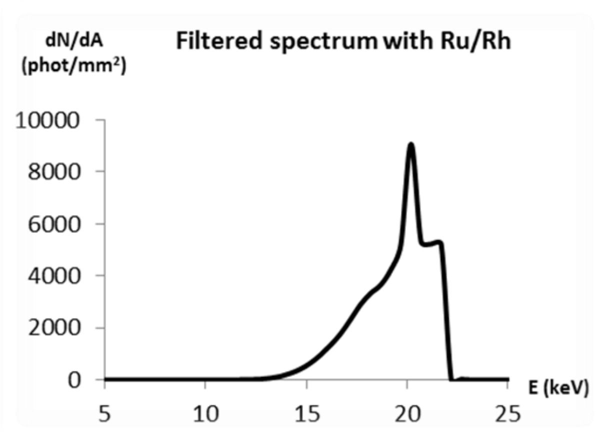


Figure 2. Rh anode spectrum with added filters 80/50 μm Ru/Rh.

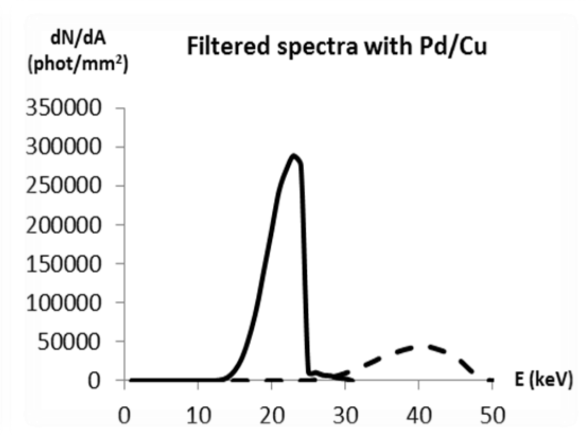
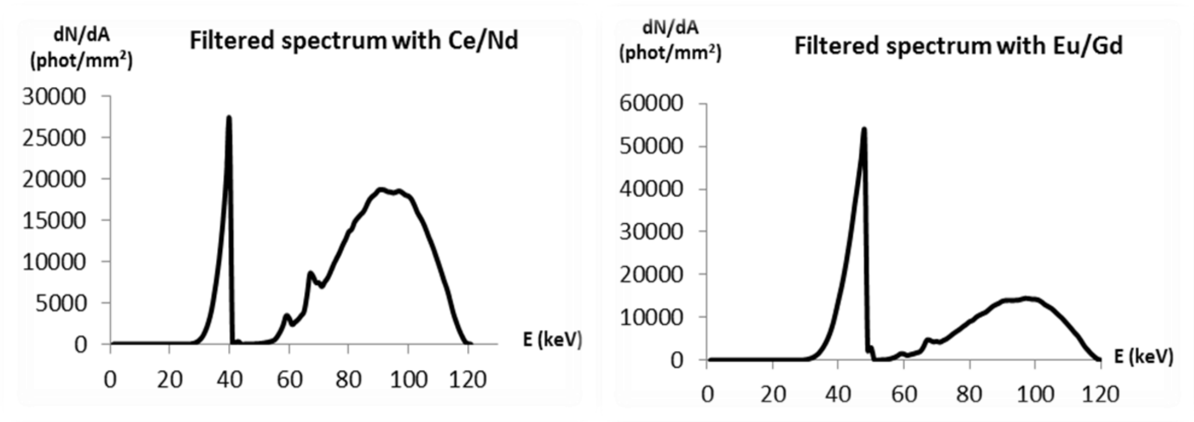


Figure 3. Double exposure W anode spectra at 30 and 50 kVp with added filtration of 55 μm Pd and 400 μm Cu.

Two methods were applied for spectra modification in bone densitometry. In the first method, single exposure with K-edge filtering was applied. Figures IV and V show two filtered W anode spectra with the same tube potentials. The different material of the filters has an impact on the spectrum in both mean energy values and total counts. For Fig. IV, the mean energy values are 37.70 keV for the low energy (LE) and 90.30 keV for the high energy (HE). The corresponding values for Fig. V are 44.25 keV for LE and 92.06 keV for HE.



Figures 4 and 5. W anode spectra at 120 kVp with added filtration of Ce/Nd and Eu/Gd 400 μm each one.

Figures 6 and 7 show double exposure W anode spectra filtered with Nd for LE and Gd/Sm for HE, Ho for LE and Ce/Nd for HE respectively. By applying the suitable K-edge filtering, a quasi-monochromatic low energy spectrum can be obtained (FWHM is lower in Nd filtration than Ho filtration).

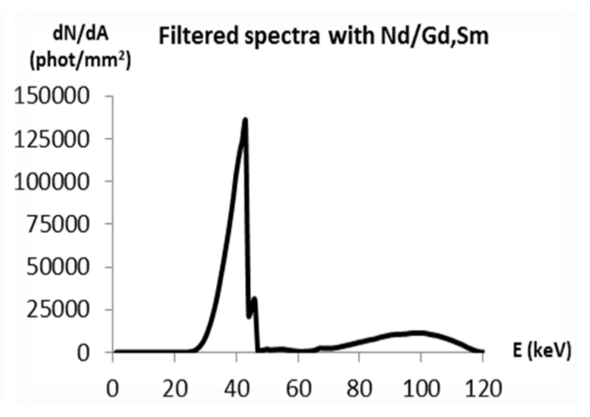


Figure 6. Double exposure W anode spectra at 60 and 120 kVp with added filtration of 500 μm Nd and 400/400 μm Gd/Sm.

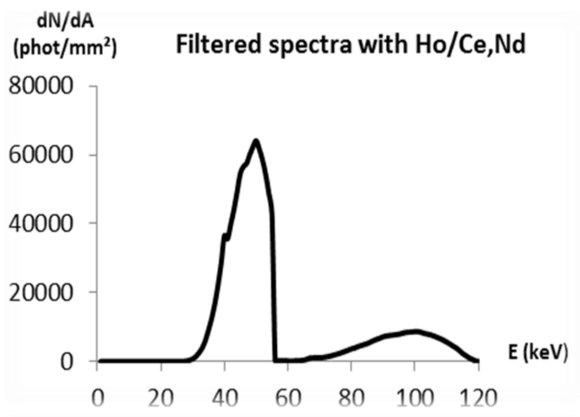


Figure 7. Double exposure W anode spectra at 60 and 120 kVp with added filtration of 450 μm Ho and 500/650 μm Ce/Nd.

4 CONCLUSIONS

Our simulations indicate that a variety of x-ray kV and anode/ K-edge filter combinations can be used for both mammography and bone densitometry, with performance characteristics comparable and in some cases better than previous studies [21, 22]. The work described in this paper demonstrates that, for both cases, using selected K-edge filters, the spectra from tungsten, molybdenum, and rhodium anode tubes can be adjusted to provide incident x-ray spectra with a high proportion of the x-rays lying within the optimum energy band. Future work of our group would be further modification of mammographic and bone densitometry spectra in order to obtain narrower spectra.

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