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Evaluation of Phantom Equivalent Materials in Polychromatic Diagnostic X-Ray Beam

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Research Article

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ABSTRACT

Background: Many phantoms are available in the market for dosimetric and quality assurance studies of radio-diagnostic and radiotherapy equipment. These phantoms are quite expensive and are seldom available in many hospitals.

Objective: The study is aimed to explore the suitability of few cost effective materials to substitute as phantoms for dosimetric study purposes.

Materials & methods: Card board and sun mica sheets were used as sample materials. Virtual water or solid water phantom was considered as the standard. Mass attenuation coefficients (μ/ρ) were experimentally determined for these samples with diagnostic x-ray beam which were then correlated with the theoretical values for monoenergetic photons to estimate the effective energies of the interacting beams. The results were verified with SpekCalc program and the published data.

Results and discussion: Cardboard and sun mica sheets exhibited μ/ρ values closer to virtual water. However, effective energies of interaction and interaction cross sections of card board are closer to virtual water than that of sun mica sheets.

Conclusion: This study showed that card board could be used as tissue equivalent phantom for dosimetric studies in diagnostic x-ray energies and hence can be explored for the manufacturing of low cost phantom material with cardboard as the major raw material.

INTRODUCTION

Though water is usually employed as a perfect tissue equivalent phantom for absolute dosimetric measurements, solid phantoms are employed for relative dosimetric studies and quality assurance measurements. Varieties of phantom materials which are quite expensive are used by the hospitals to accomplish these measurements. Publications on the analysis and compositions of various phantom materials are available in the literature [1-8]. This study attempts to determine the mass attenuation coefficients (μ/ρ) of a few materials experimentally and to calculate the total photon interaction cross section (σ_{tot}) of these samples with the polychromatic beam of diagnostic x-ray photon beam and evaluate their suitability to be substituted for phantom materials.

MATERIALS AND METHODS

A 100 mA x-ray unit (SIEMENS/Multimobile 10) was chosen for the study. The x-ray unit was initially tested for quality assurance before employing it for actual study.

Card board and Sun mica were the sample materials chosen for this study. These samples were cut into rectangular blocks/sheets. Thicknesses of the materials were measured using screw gauge.

Virtual water, also known as solid water phantom which is composed of 77.5% of Carbon, 10% of Hydrogen, 5% of Oxygen, 3.5% of Nitrogen, 2.5% of Fluorine and 1.5% Calcium was used as standard. These blocks are designed by M/s. Med-Tec, USA and are available in rectangular blocks of 30 cm^2 area with thicknesses ranging from 0.5 cm to 3.5 cm.

RAD-CHECK PLUS [Model: 06-526-2200] x-ray exposure meter, designed by Fluke Biomedical, USA was used for the purpose of measuring the integrated exposure of the polychromatic diagnostic x-ray beam. This instrument has a built-in ionization chamber of 30 cc cylindrical volumes with 5.1 cm diameter thus giving an effective measurement area of 20.5 cm^2 circular area. This has an energy response of ± 5% from 15 keV to 65 keV (30 kVp to 150 kVp filtered). The instrument is capable of measuring the radiation exposure for a range of 0.01 mGy to 19.99 mGy.

EXPERIMENTAL SET-UP

The experimental arrangement for attenuation measurement for all the samples is shown in **Figure 1**. A stand was fabricated to place the samples in such a way that a distance of around 30 cm is maintained between the focus and the absorbers and a minimum of 20 cm is maintained between the absorbers and the detector to avoid scattered photons and secondary electrons reaching the detector.

Figure 1. Experimental set up.

The x-ray beam was collimated in such a way that the light field just covers the detector area of the RAD-CHECK PLUS x-ray exposure meter at 60 cm focus to chamber distance. In this way the x-ray intensity transmitted though the samples could reach the detector without any hindrance.

At tube setting of 16 mAs, incident intensity (I0) and the transmitted intensity (I) were measured for the peak voltages of 70 KVp and 85 KVp for each set of sample materials. The attenuation measurements of each sample were thus measured by placing the blocks/sheets one over the other after each measurement.

The mass attenuation coefficients (μ/ρ) of each sample material were determined by the following popular relationships, viz,

$$I=I_0 e^{-(\mu/\rho)(\rho x)} \quad \text{eq (1)}$$

$$\text{and } HVL=\frac{0.693}{\mu} \quad \text{eq (2)}$$

where ρx is the thickness of the absorber expressed in g/cm^2, HVL is the Half Value Layer (HVL), which is the thickness of the absorber required to reduce the transmitted intensity to 50% of the incident intensity [9].

ENERGY DISPERSIVE X-RAY (EDX) ANALYSIS

Energy Dispersive X-ray Analysis, also referred as EDS or EDAX, is a chemical microanalysis technique used together with a Scanning Electron Microscope (SEM). This detects x-rays emitted from the sample during bombardment by an electron beam to characterize the elemental composition of the sample. All elements from atomic number 4 (Be) to 92 (U) can be detected in principle. Quantitative analysis entails measuring line intensities for each element in the sample. The overall analytical accuracy is commonly nearer to +2%. The equipment view is shown in **Figure 2**.

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Figure 2. EDX Spectrometer with SEM.

The samples which are electrically non-conducting are coated with a conducting surface to provide a path for the incident electrons to flow to ground. EDX spectrometers employ pulse height analyzer which gives output pulses proportional in height to the X-ray photon energies.

The ED spectrum is displayed in digitized form with the x-axis representing X-ray energy and y-axis representing the number of counts per channel. The elements present in the sample specimen are identified by the lines in the X-ray spectrum using tables of energies or wavelengths and qualitative analysis is obtained from the complete ED spectrum.

The sample specimens of the materials have been prepared and subjected to the EDX analysis. The compositions of elements in each sample have been determined using this analysis and they have been tabulated from 1.1 to 1.5 under **Tables 1a and 1b**.

Table 1a. Elemental compositions of sample materials as determined by EDX analysis (Cardboard).

Element	App	Intensity	Weight %	Weight %	Atomic %
	Conc.	Corrn.		Sigma	
C K	3.92	1.891	97.13	2.18	98.13
O K	0.01	0.275	1.71	2.01	1.3
F K	0	0.226	0.49	0.84	0.31
Mg K	0	0.901	0.08	0.14	0.04
Si K	0	1.002	0.13	0.13	0.06
S K	0	0.994	0.16	0.17	0.06
Cl K	0	0.841	0.23	0.18	0.08
K K	0	1.041	0.05	0.14	0.02
Total			100		

Table 1b. Elemental compositions of sample materials as determined by EDX analysis (Sun mica sheet).

Element	App	Intensity	Weight %	Weight %	Atomic %
	Conc.	Corrn.		Sigma	
C K	8.64	1.06	55.43	1.25	66.05
O K	1.98	0.401	33.68	1.2	30.13
Na K	0.03	0.784	0.24	0.11	0.15
Al K	0.07	0.841	0.58	0.09	0.31
Si K	0.16	0.911	1.22	0.11	0.62
S K	0.06	0.958	0.39	0.09	0.18
K K	0.01	1.071	0.04	0.07	0.01
Ca K	0.07	1.015	0.5	0.09	0.18
Ti K	0.94	0.809	7.92	0.31	2.37
Total			100		

Mass attenuation coefficients (μ/ρ) of the sample materials were evaluated using equation (1) or (2) from the above measurements. Theoretical mass attenuation coefficients (μ/ρ) of these samples were also estimated using the XMuDat computer program developed by Nowotny [10] by entering the elemental compositions determined by the EDX method and also based on the published data [11,12]. Densities in g/cm^3 were measured for all the sample materials.

The experimental μ/ρ values were compared with these theoretical values and the energies corresponding to these values, i.e., the effective energies of the beams used were evaluated. The results confirmed that the effective energy of the interacting x-ray photons reaching the detector after attenuation is different for different materials.

The effective energies estimated by x-ray attenuation measurements of card board, sun mica sheet and virtual water in this study were verified with the effective energies estimated by the SpekCalc program. The publications of Poludniowski and colleagues [13,14] and their proposed SpekCalc program [15] were found to be very useful in evaluating the experimental results. SpekCalc is a Window based computer program applicable to an x-ray generator up to peak voltage of 120 KVp with options of additional filters of aluminium, copper, tin, tantalum, tungsten and water. This program estimates the effective energy, average energy, HVLs, bremsstrahlung output and the x-ray spectrum if exposure parameters and conditions are provided to the program window. The experimental parameters used for the sample materials in this study were fed to the program window to obtain the corresponding estimated theoretical x-ray spectrum and other characteristics associated with the spectrum including the effective energies. The thicknesses in mm of these samples were entered as thicknesses in water in the SpekCalc program window.

RESULTS AND DISCUSSION

Tables 2a-2c list the attenuation measurements of samples with x-ray beam from which attenuation curves have been obtained. One such plot of attenuation curves obtained for card board at the peak voltages of 70 kVp and 85 kVp and the one obtained for virtual water are shown in **Figures 3 and 4,** respectively. The mass attenuation coefficients (μ/ρ) determined from the experimental measurements, the total photon interaction cross-sections (σtot) calculated based on these experimental μ/ρ values and the estimated effective energies of the beam for the two sets of peak voltages are shown in **Table 3**.

Table 2a. Attenuation measurements (in mGy) (x-ray tube setting: 16 mAs) for Cardboard (ρ=0.7567 g/cm^3).

Thickness (cm)	70 KVp, 16 mAs	85 KVp, 16 mAs
0.0	1.36	2.02
1.0	1.03	1.71
1.9	0.80	1.44
2.8	0.63	1.21
3.9	0.50	1.02
4.8	0.40	0.86
5.7	0.32	0.73
7.8	1.36	2.02

Table 2b. Attenuation measurements (in mGy) (x-ray tube setting: 16 mAs) for sun mica sheet (ρ=1.121 g/cm^3).

Thickness (cm)	70 KVp, 16 mAs	85 KVp, 16 mAs
0.00	1.36	2.02
0.55	1.11	1.69
1.10	0.91	1.42
1.53	0.75	1.20
2.27	0.62	1.01
2.69	0.52	0.86
3.15	0.46	0.78

Table 2c. Attenuation measurements (in mGy) (x-ray tube setting: 16 mAs) for virtual water blocks (ρ=1.11 g/cm^3).

Thickness (cm)	70 KVp, 16 mAs	85 KVp, 16 mAs
0.0	1.210	1.860
0.5	0.995	1.570
1.0	0.840	1.355
1.5	0.705	1.160
2.0	0.600	0.990
2.5	0.505	0.845
3.0	0.430	0.730
3.5	0.365	0.630

Figure 3. Attenuation curve for cardboard.

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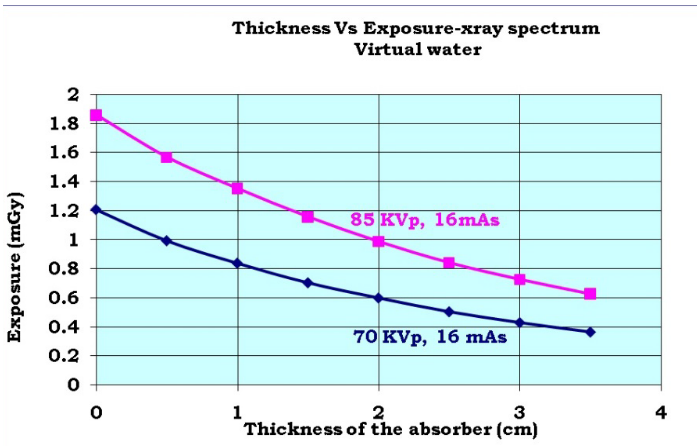

Figure 4. Attenuation curve for virtual water.

Table 3. Experimental values of mass attenuation coefficients, total photon interaction cross sections and effective energies.

Sample	70 kVp			85 kVp		
	μ/ρ (cm²/g)	σ_{tot} (barns/atom)	Effective energy (keV)	μ/ρ (cm²/g)	σ_{tot} (barns/atom)	Effective energy (keV)
Card board	0.374	7.177	23.1	0.232	4.451	36.7
Sun mica sheet	0.326	8.449	45.3	0.272	7.071	52.2
Virtual Water	0.312	6.122	32.7	0.284	5.565	35.7

The variation of the experimental photon mass attenuation coefficients with the estimated effective energies were plotted for all the samples. One such plot for card board and the one obtained for virtual water are shown in **Figures 5 and 6**.

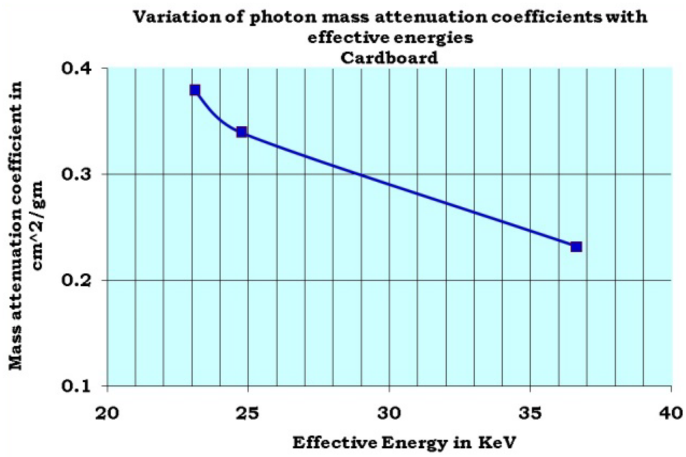

Figure 5. Attenuation coefff and eff energies for card board.

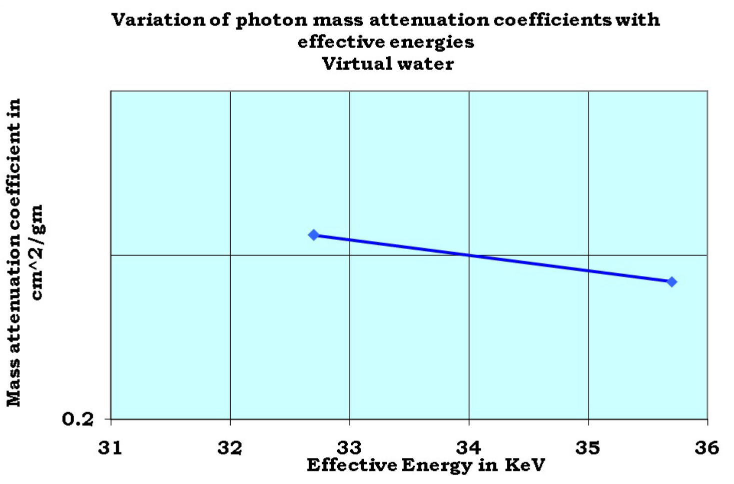

Figure 6. Attenuation coeff and eff energies for virtual water.

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ESTIMATION OF ERRORS

Diagnostic x-ray calibrations require less accuracy (typically +10%), but must be capable of measuring low exposures at high intensities which implies that a relatively large chamber volume with high electric field intensity to prevent ion recombination should be selected for x-ray output measurements. The recommended chamber volume should not be more than 100 cm^3 [16]. RAD-CHECK PLUS has an in built ionization chamber of 30 cm^3.

The uncertainties involved in attenuation measurements for diagnostic x-ray energy ranges may be due to the wide beam geometry covering the 30 cc volume of the detector chamber of 20.5 cm^2 circular areas at 60 cm focus to chamber distance (FCD), thus detecting scatter photons also. However, de Sousa Lacerda et al. [17] quantified the uncertainties due to chamber volume of 60 cc with paper as scattering medium to 7.8 %, with lead to 1.2%, with table of the x-ray unit to 4.1% and in air to 2.5%. Since the chamber volume of RAD-CHECK PLUS is only 30 cc and the atomic numbers of all samples used in this study are in the range of 7 to 14, uncertainties due to scatter in this study should be less. Combinations of focus to chamber distance (FCD) and focus to absorber distance (FAD) also influence the accuracy of measurements. The experimental set up 60 cm FCD and 30 cm FAD employed in this study would lead to an uncertainty of -1.2% as reported by de Sousa Lacerda et al. [17]. Thus the inaccuracies in the estimation of effective energies of diagnostic x-ray beam with the samples in air due to scatter is expected to be less than 3%.

The percentage variations of the SpekCalc estimation to the experimental estimation of effective energies were obtained for all the samples at the peak voltages (70 kVp and 85 kVp) used in this study. The theoretical x-ray spectrum and other characteristics associated with the spectrum including the effective energies for the three samples in study at 70 kVp x-ray beam are depicted in **Figures 7a-7c**. The SpekCalc program was used. The percentage deviation is less than 5% for virtual water establishing that the experimental method did not suffer from wide uncertainties. However, in the case of card board and sun mica sheet, these variations are wide, with a maximum deviation of 41.8% at 85 kVp for sun mica sheets. But these variations were mainly due to the fact that the sample thicknesses were entered as water thicknesses in the program window and hence these variations could not be attributed to experimental errors. These results are shown in **Table 4**.

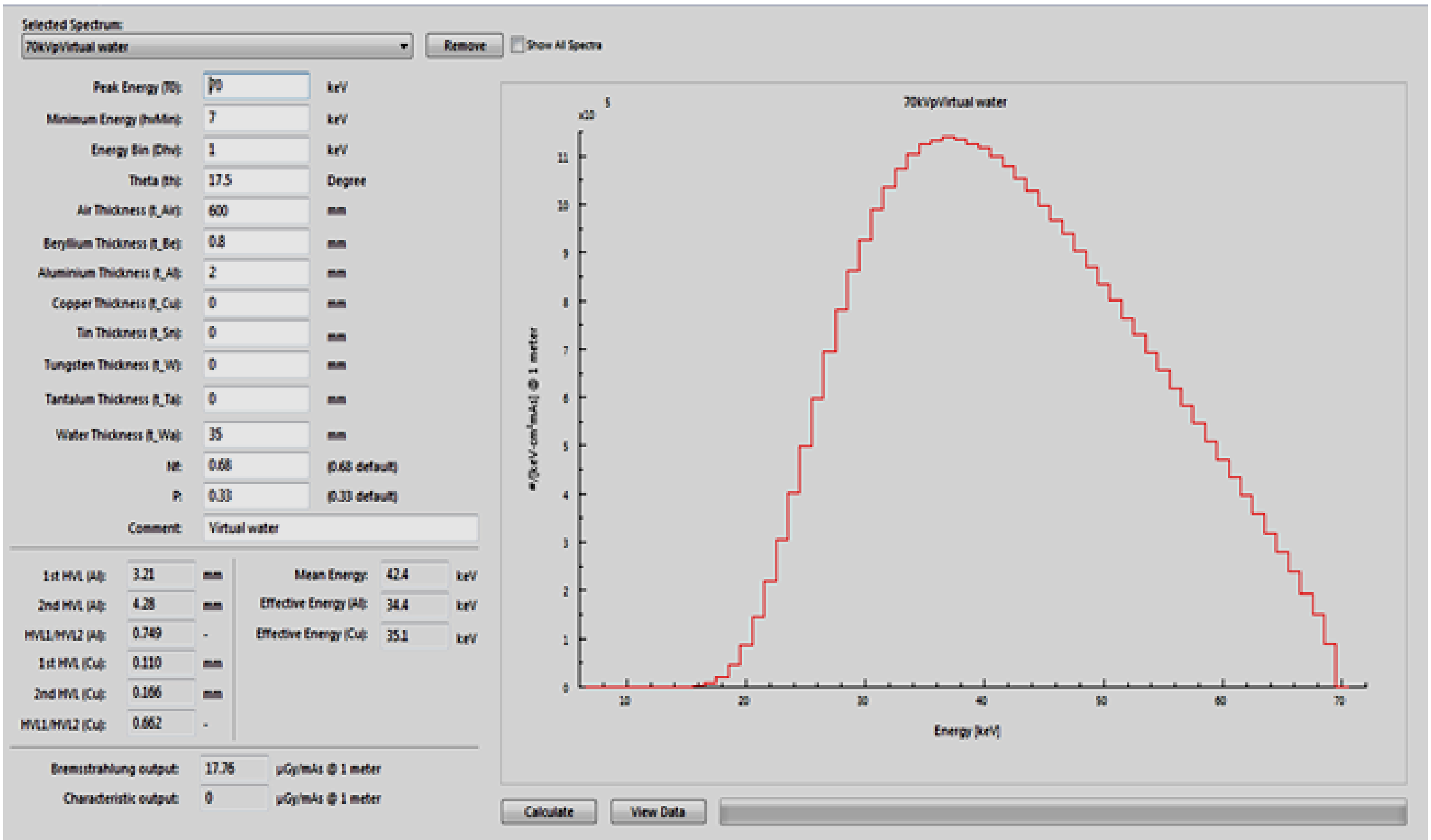

Figure 7a. X-ray Spectrum and effective energies estimated by SpekCalc computer program for virtual water at 70 kVp.

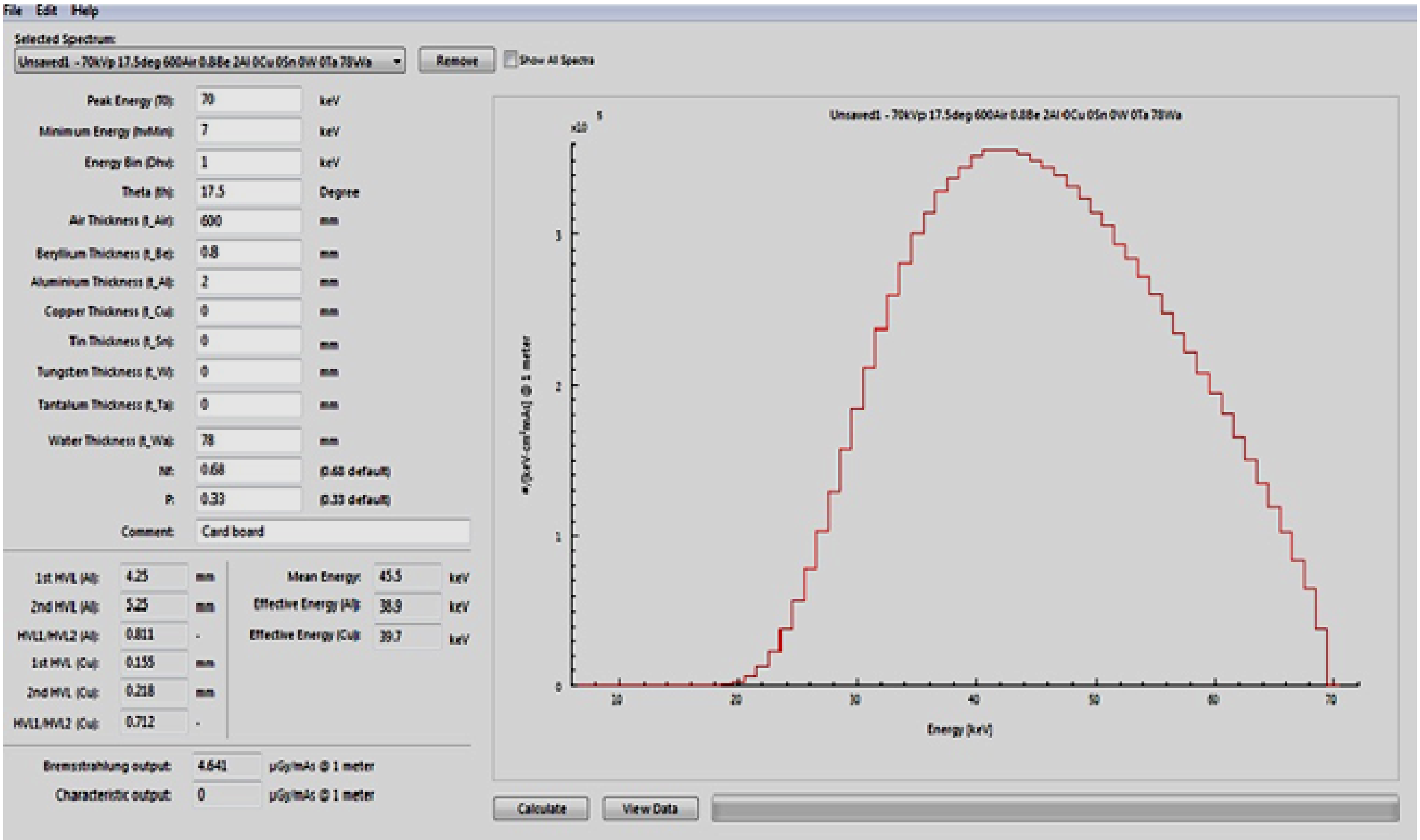

Figure 7b. X-ray Spectrum and effective energies estimated by SpekCalc computer program for card board at 70 kVp.

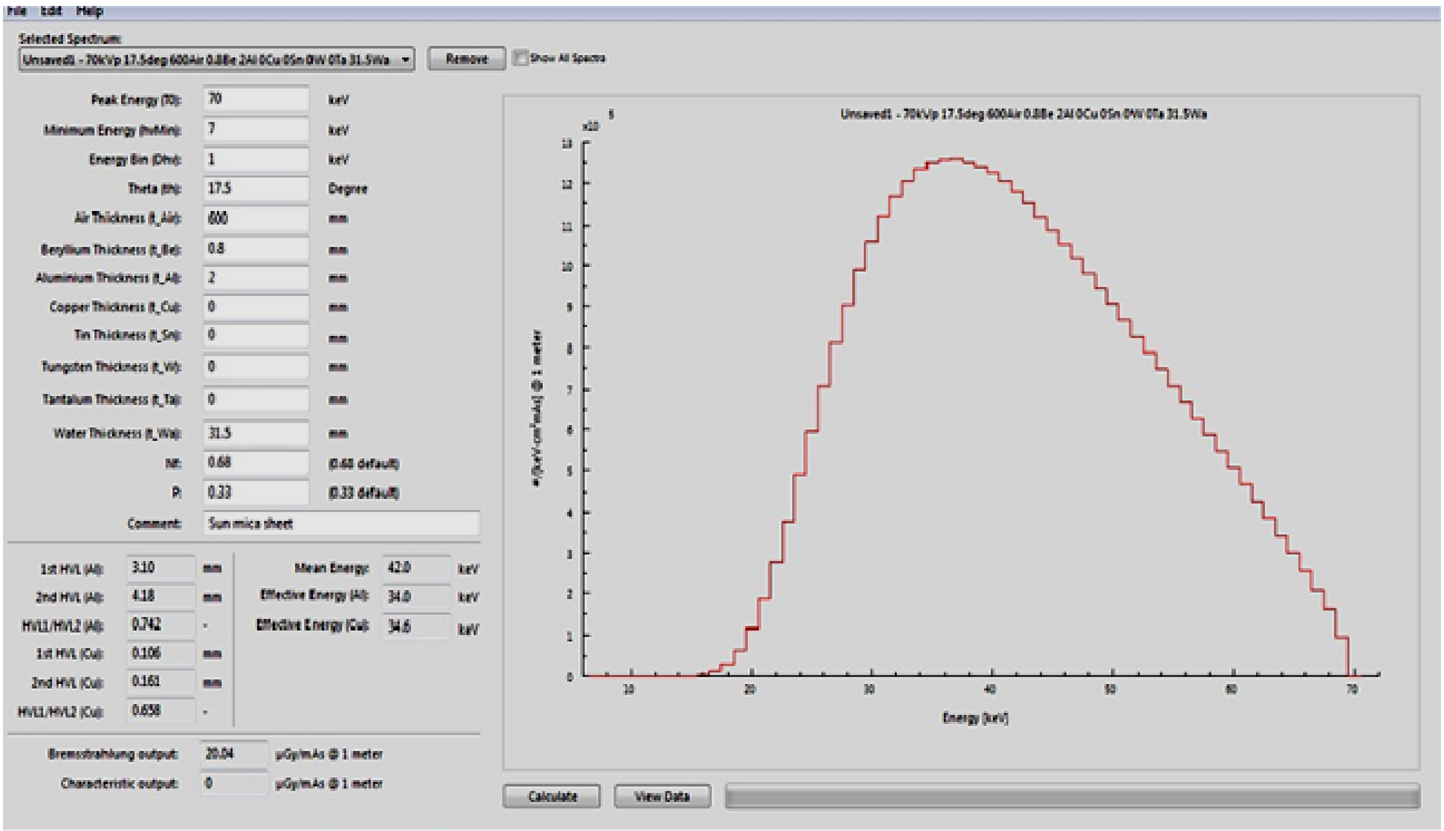

Figure 7c. X-ray Spectrum and effective energies estimated by SpekCalc computer program for sun mica sheet at 70 kVp.

Table 4. Experimental effective energies and effective energies estimated by spekcalc computer program.

Sample	Estimated effective energy				Percentage deviation	
Material	This study		SpeckCalc		SpeckCalc vs. Experimental	
	70 kVp	85 kVp	70 kVp	85 kVp	70 kVp	85 kVp
Virtual water	32.7	35.7	34.4	37.3	-4.9	-4.3
Card board	23.1	36.7	38.9	42.7	-40.6	-14.1
Sun mica	45.3	52.2	34	36.8	33.2	41.8

The μ/ρ values determined for card board and sun mica were closer to those values obtained for virtual water. In the case of card board, the effective energies and interaction cross sections obtained were also closer to those values of virtual water compared to those values obtained for sun mica sheets. The study suggested that card board could function as tissue equivalent phantom for dosimetric studies in the diagnostic x-ray energy ranges and it can be used in those installations where phantoms like solid water are not available. Design of tissue equivalent phantoms with card board as a major raw material can also be explored which will be cost effective.

CONCLUSION

The polychromatic diagnostic x-ray beam with wide beam geometry was considered for the study because of its wide applications in the branch of medicine. The beams were used with their inherent heterogeneities and complexities in order to find out the effective energies in the same way as they are used on the human population.

The attenuation measurements established the predominance of photoelectric absorption in diagnostic x-ray energies. The values obtained were evaluated with SpekCalc computer program and the percentage deviations between these two estimations showed a maximum deviation of 41.8 % at 85 kVp for sun mica sheets.

The study suggested the suitability of card board to function as tissue equivalent phantom and its application in the designing of low cost tissue equivalent phantoms. The study can also be extended to with other materials for the estimation of shielding thicknesses for radiation protection activities based on the effective energies of the polychromatic beams instead of mean energy which is generally considered in the case of heterogeneous energy spectrum.

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