X- and γ-ray interaction characteristics of Griffith, Alderson, Frigerio, Goodman and Rossi tissue substitutes

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Abstract

Detailed information of radiation interaction, exposure and dose delivery to tissue substitutes is necessary for various branches of radiation physics. In the present investigation X- and γ-ray interaction characteristics of some tissue substitutes such as Griffith, Alderson, Frigerio, Goodman and Rossi have been studied and compared with standard tissues. Effective atomic numbers and air-kerma have been computed using mass attenuation coefficients and mass energy-absorption coefficients, respectively. Energy-absorption buildup factors for photon energy 0.015 to 15 MeV up to 40 mean free path were calculated using G-P fitting method. These investigations provide further information on the X- and γ-ray interaction of tissue substitutes for various applications in radiation physics and medical physics.

Keywords: Tissue substitutes, X- and gamma-ray, Buildup factors, Effective atomic numbers.

1.-INTRODUCTION

Photon interaction with human tissues, tissue substitutes and dosimeters is defined by parameters such as mass attenuation coefficients, effective atomic numbers, effective electron densities, kinetic energy released per unit mass (kerma) and buildup factors. The photon buildup factors areexposure buildup factors and energy absorption buildup factors. The effective atomic numbers and effective electron densities are estimated for a compound or composite material using mass attenuation coefficients of the elements. The kinetic energy released per unit mass of a compound or composite material is calculated by using mass-energy absorption coefficients of elements.

The intensity of a narrow mono-chromatic gamma-ray beam through a thin absorbing material follows Lambert's Beer law. In case of change in conditions of following conditions, Lambert's Beer law is corrected by a multiplication correction factor called as "buildup factor". The buildup factors of elements are found to be very high for low- atomic numbers. Exposure buildup factors and energy absorption buildup factors of isotropic point sources are widely used for dose estimations in medical applications for water and PMMA phantoms and in gamma-ray shielding applications.

In the present work, we have investigated effective atomic numbers, air-kerma and energy absorption buildup factors for tissues substitutes [ICRU 1989]. The effective atomic number and air-kerma values were compared with standard ICRU tissues. The results of the present work could be useful in themedical applications.

2.-MATERIAL AND METHODS

The investigation on photon interaction characteristics was accomplished for tissue substitutes Griffith, Alderson, Frigerio, Goodman and Rossi along with ICRU standard tissues. The detailed of these tissue substitutes and standard tissues is given in ICRU report [ICRU 1989].The compositions of these materials is given in Table 1.

Table.1. Elemental compositions of tissue substitutes and ICRU tissues

Description	ID	H	C	N	O	Na	Mg	P	S	Cl	K	Ca	Sb
Griffith breast	Gr-Br	9.4	61.9	3.6	24.5							0.6	
Griffith lung	Gr-Lg	8	60.8	4.2	24.8		0.1					2.1	
Griffith muscle	Gr-Mc	9	60.2	2.8	26.6							1.4	
Alderson lung	Al-lg	5.7	74	2	18.1								0.2
Alderson muscle A	Al-McA	8.9	66.8	3.1	21.1								0.1
Alderson muscle B	Al-McB	8.8	64.4	4.1	20.4					2.2			0.1
Fregerio gel	Fr-Gl	10	12	4	73.3	0.4			0.2	0.1			
Fregerio liquid	Fr-Ld	10.2	12.3	3.5	72.9	0.1		0.2	0.3	0.1	0.4		
Goodman liquid	Gm-Ld	10.2	12	3.6	74.2								
Rossi gel	Rs-Gl	9.8	15.7	3.6	70.9								
Rossi liquid	Rs-Ld	9.8	15.6	3.6	71								
ICRU breast	ICRU-Br	10.6	33.2	3	52.7	0.1		0.1	0.2	0.1	0		
ICRU lung	ICRU-Lg	10.3	10.5	3.1	74.9	0.2		0.2	0.3	0.3	0.2		
ICRU muscle	ICRU-Mc	10.2	14.3	3.4	71	0.1		0.2	0.3	0.1	0.4		

2.2.-Effective atomic number

Total atomic cross-section (σ_t) for a compound or composite is obtained from the following relation;

$$\sigma_t = \frac{\mu_m M}{N_A} \qquad (1)$$

where $M = \sum_i^n n_i A_i$ is the molecular weight of the compound, N_A is the Avogadro's number, and μ_m is total mass attenuation coefficients, thatis calculated using mixture rule as $\mu_m = (\mu/\rho) = \sum_i^n w_i(\mu/\rho)_i$, where w_i is the proportion by weight and $(\mu/\rho)_i$ is mass attenuation coefficient of the ith element. The μ/ρ values of individual element were taken from user-friendly Windows based WinXcom program [Gerward *et al.*, 2004].

Effective atomic numbers of a compound or mixture is calculated by the ratio of effective atomic cross section (σ_a) and effective electronic cross section (σ_e). The calculation procedures for $\sigma_e$and σ_e are given literature [Singh and Badiger 2015].

The effective atomic cross section (σ_a) is calculated using the following equation:

$$\sigma_a = \frac{1}{N_A} \sum f_i A_i (\frac{\mu}{\rho})_i \tag{2}$$

The effective electronic cross-section (σ_e) is calculated using the following equation;

$$\sigma_e = \frac{1}{N_A} \sum \frac{f_i A_i}{Z_i} (\frac{\mu}{\rho})_i = \frac{\sigma_a}{Z_{eff}} \tag{3}$$

where $f_i = \frac{n_i}{\sum_i n_i}$ denotes the mole fraction of element *i* with respect to the number of atoms such that $\sum_i^n f_i = 1$, Z_i is the atomic number of *i*th element.

2.2.- Air-kerma

Air-kinetic energy released per unit mass (kerma) is the ratio of mass-energy absorption coefficients of a compound or mixture to the air. It is defined as following relation;

$$K_a = \frac{K_{sample}}{K_{Air}} = \frac{(\mu_{en}/\rho)_{sample}}{(\mu_{en}/\rho)_{Air}} \tag{4}$$

The values ofthe mass energy absorption coefficient, μ_{en}/ρ of a compound or the composite and air are calculated by using the mixture rule ($\frac{\mu_{en}}{\rho} = \sum_i w_i (\frac{\mu_{en}}{\rho})_i$), where w_i and $(\mu_{en}/\rho)_i$ are the weight fraction and the mass energy absorption coefficient of the i^{th} element. The values of $(\mu_{en}/\rho)_i$ have been taken from the literature [NIST 2009].

2.3.-Energy absorption buildup factors

The ANSI/ANS-6.4.3, 1991 report [ANS 1991] is published by the American Nuclear Society; a compilation of buildup factors at energies 0.015–15 MeV, and for penetration depths up to 40 mean free paths (mfp) for the elements Z = 4–92.A five-parameter fitting formula, called Geometric Progression (G-P) was developed by Harima *et al* [1986], which gives the buildup factors for a compound or mixture. The G-P fitting formula is also found in literature of Harima [1993]. The buildup factors B (E, x) are calculated from the following equations [Harima 1993]:

$$B(E,x) = 1 + \frac{b-1}{K-1}(K^{X} - 1)\text{, for K} \neq 1, \tag{5}$$

$$B(E,x) = 1 + (b-1)x\text{, for K = 1,} \tag{6}$$

$$K(E,x) = cx^{a} + d\,\frac{\tanh(x/X_{K} - 2) - \tanh(-2)}{1 - \tanh(-2)}, \tag{7}$$

where*E* is the source energy, x is the penetration depth in units of mfp, and *a, b, c, d* and X_K are the G-P fitting parameters. The mfp parameter, or the relaxation length is reciprocal of linear attenuation coefficients (x = 1/μ), where μ is linear attenuation coefficient (cm^{-1}).

3.- RESULTS AND DISCUSSION

The effective atomic numbers ofthe selected tissues along with ICRU standard tissues is shown in Fig.1. The air-kermaof the selected tissues and ICRU standard tissues are shown in Fig.2. The energy absorption buildup factors of the selected tissue substitutes are shown in Fig.3. The variation of these parameters with photon is explained separately.

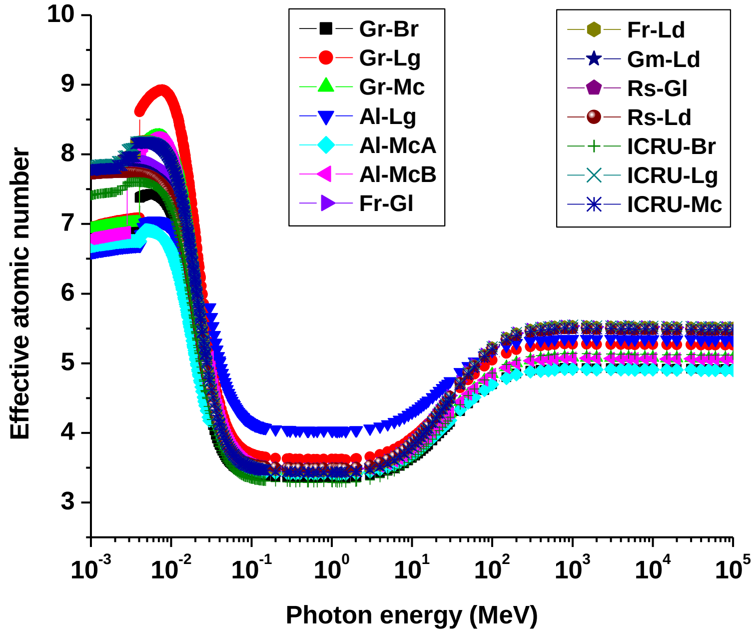


Figure 1. Effective atomic numbers of tissues substitutes and ICRU standard tissues

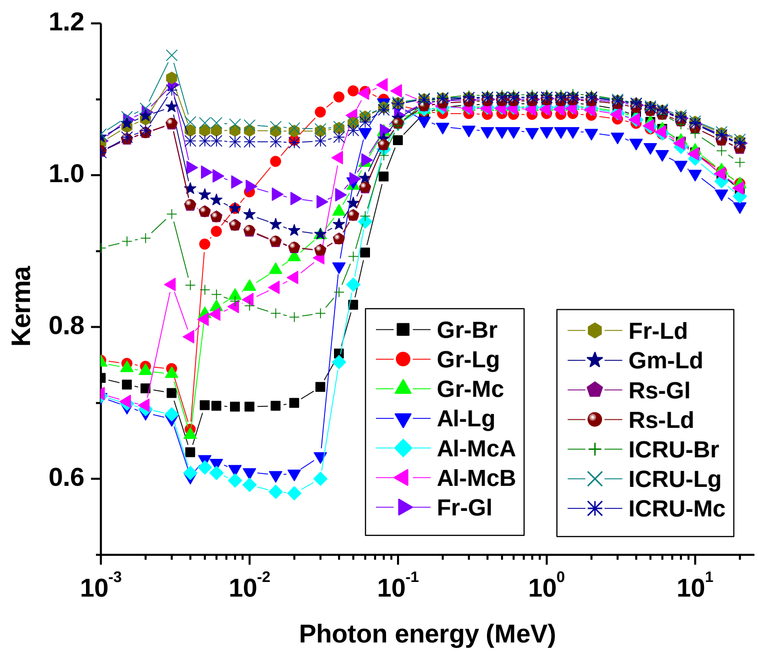
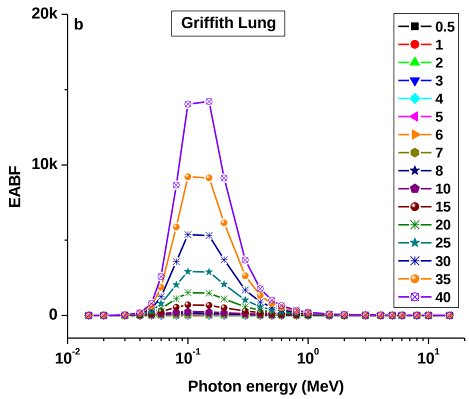


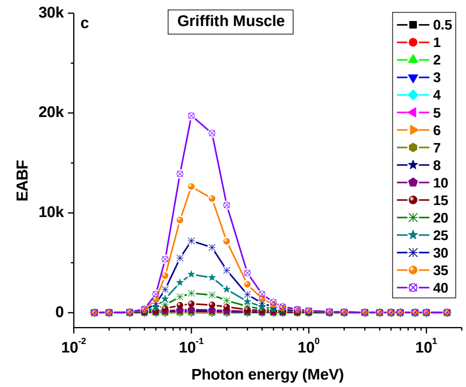
Figure 2. Air-kerma of tissues substitutes and ICRU standard tissues

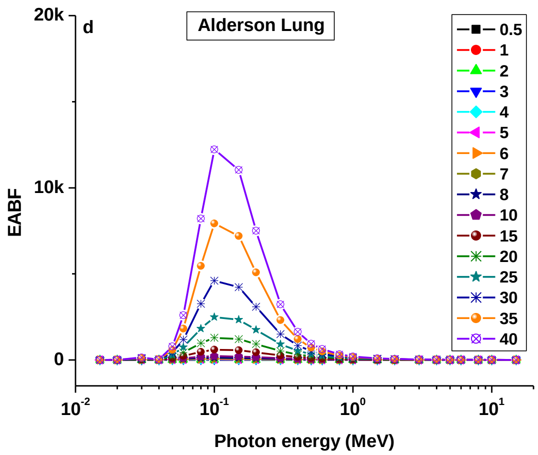
The effective atomic numbers (Z_{eff}) of selected tissue substitutes, Griffith, Alderson, Frigerio, Goodman and Rossi and ICRU standard tissues for photon energy 1 keV to 100 GeVare shown in Fig.1. In general the variations of Z_{eff} of tissue substitutes and standard tissues are similar in nature and magnitude for entire energy region. The variation of Z_{eff} is found to be such that it is the lowest in intermediate-energy region, whereas it is the highest in low- and slightly higher in the high-energy region.The variation of Z_{eff} is explained using dependency of partial photon interaction cross section on photon energy and atomic number of the elements.The partial photon interactions processes are photoelectric effect, Compton scattering and pair production. The explanations for variation of Z_{eff} using partial interaction is found in various literature.Fig.1 shows that the Z_{eff} values of tissue substitutes are comparable with standard ICRU tissues. Therefore, it is possible to replace the ICRU standard tissues (breast, lung and muscle) with the selected tissue substitutes.

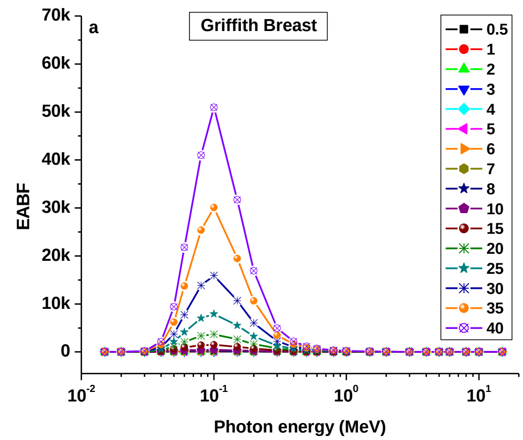
Air-kerma of the selected tissue substitutes, Griffith, Alderson, Frigerio, Goodman and Rossi and ICRU standard tissues for photon energy 1 keV to 15 MeV is shown in Fig.2. In general, air-kerma of tissue substitutes and standard tissues is found to be in range of unity. Below 100 keV photon energy, the variation in air-kermais observed to be larger whereas the air-kermavalues begin decreasing above 5 MeV photon energy for all the tissue substitutes and tissues.Major change in air-kerma is found to be below photon energy of 100 keV where photoelectric effect is dominant interaction process.

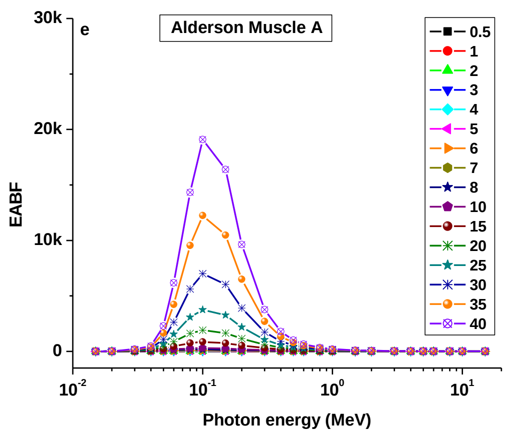
The energy absorption buildup factor (EABF) of selected tissue substitutes, Griffith, Alderson, Frigerio, Goodman and Rossi for photon energy 0.015 to 15 MeV for penetration depths up to 40 mean free path is shown in Fig. 3, here it is found to be that the EABF of all the tissue substitutes are small in low- and high- energy of photon with a peak in intermediate- energy of photon.The EABF of tissue substitutes is found to be increasing with increase in penetration depths of the tissue substitutes.This variation of EABF is explained by partial photon interactions similar to the effective atomic numbers and air-kerma.

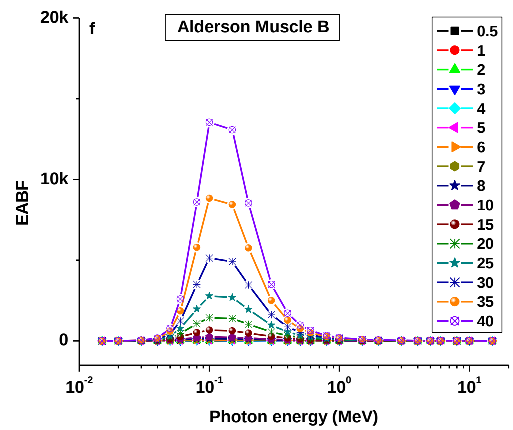

b
Griffith Lung
20k
10k
0
EABF
10^{-2}
10^{-1}
10^{0}
10^{1}
Photon energy (MeV)
0.5
1
2
3
4
5
6
7
8
10
15
20
25
30
35
40


c
Griffith Muscle
30k
20k
10k
0
EABF
10^{-2}
10^{-1}
10^{0}
10^{1}
Photon energy (MeV)
0.5
1
2
3
4
5
6
7
8
10
15
20
25
30
35
40


d
Alderson Lung
20k
10k
0
EABF
10^{-2}
10^{-1}
10^{0}
10^{1}
Photon energy (MeV)
0.5
1
2
3
4
5
6
7
8
10
15
20
25
30
35
40


a
Griffith Breast
70k
60k
50k
40k
30k
20k
10k
0
EABF
10^{-2}
10^{-1}
10^{0}
10^{1}
Photon energy (MeV)
0.5
1
2
3
4
5
6
7
8
10
15
20
25
30
35
40


e
Alderson Muscle A
30k
20k
10k
0
EABF
10^{-2}
10^{-1}
10^{0}
10^{1}
Photon energy (MeV)
0.5
1
2
3
4
5
6
7
8
10
15
20
25
30
35
40


f
Alderson Muscle B
20k
10k
0
EABF
10^{-2}
10^{-1}
10^{0}
10^{1}
Photon energy (MeV)
0.5
1
2
3
4
5
6
7
8
10
15
20
25
30
35
40

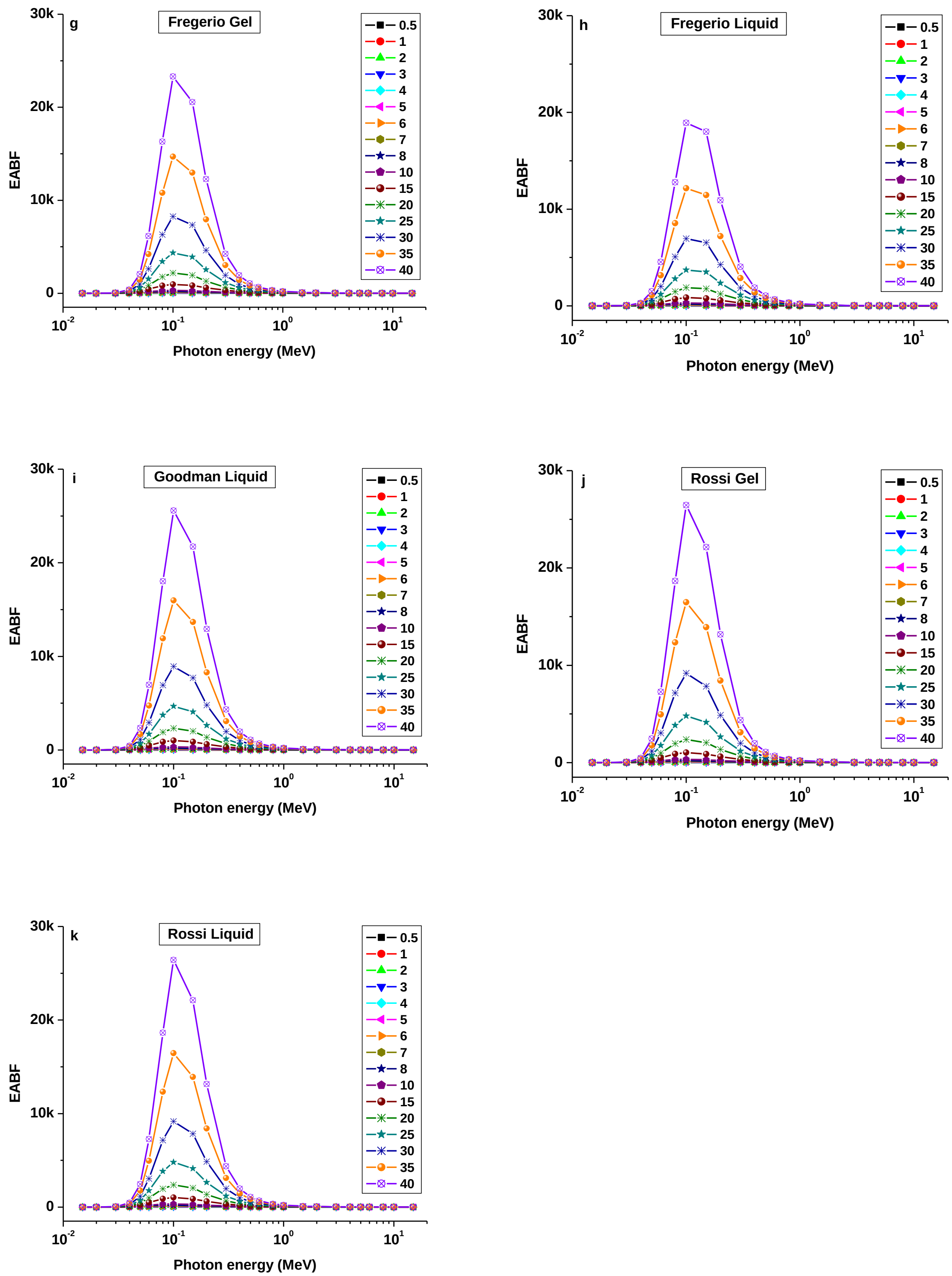


Figure 3. Energy absorption buildup factors of tissues substitutes

The EABF in low-energy photon is small because the all the photons are completely removed by photoelectric effect and EABF in high-energy photon is also due to pair production where photon removal and generation processes take place. Peak EABF is observed in intermediate-energy of photon because the photon buildup due to scattering process of photons. During Compton scattering process, after each interaction, a low-energy photon is generated.The EABF increases with penetration depths because the large penetration depths offer large thickness of tissues for multiple scattering processes, which results in buildup of the photons. Detailed explanation of EABF can be referred in literature elsewhere.

4.- CONCLUSION

In the present investigation, photon interaction characteristics of some tissue substitutes, Griffith, Alderson, Frigerio, Goodman and Rossi was studied using effective atomic numbers, air-kerma and energy absorption buildup factors. The using effective atomic numbers and air-kerma of tissue substitutes were compared with ICRU standard tissues and found comparable. The photon interaction parameters were described using partial photon interaction processes. It was observed that the effective atomic numbers reduces to minima values in intermediate-energy region andair-kerma is constant whereas energy absorption buildup factor is the highest.

REFERENCES

ANS, (1991). *Gamma ray attenuation coefficient and buildup factors for engineering materials*. **ANSI/ANS-6.4.3**, American Nuclear Society. Illinois, USA.

Gerward L, Guilbert N, Jensen KB, Levring H. (2004). *WinXCom-a program for calculating x-ray attenuation coefficients*. Radiation Physics and Chemistry **71**: 653-654.

Harima, Y.; Sakamoto, Y,; Tanka, S.; Kawai, M. (1986). *Validity of the geometrical progression formula in approximating gamma-ray buildup factors*. Nuclear Science and Engineering **94**: 24-35.

Harima, Y. (1993). *An historical review and current status of buildup factor calculation and applications*. Radiation Physics and Chemistry **41**: 631-672.

ICRU. (1989). *Tissue substitutes in radiation dosimetry and measurement*. **ICRU report 44**, International commission on Radiation units and measurement. Bethesda, USA.

NIST. [Online]. Hubbell, J.H. and Seltzer, S.M. *Tables of x-ray mass attenuation coefficients and mass energy-absorption coefficients from 1 keV to 20 MeV for elements Z = 1 to 92 and 48 additional substances of dosimetric interest*. (2009). < http://www.nist.gov/pml/data/xraycoef/>. [Accessed on September 2014].

Singh, V.P.; Badiger N.M. (2015). *Studies on Photon buildup for some thermoluminiscentdosimetric compounds*. Indian Journal of Physics. Doi: 10.1007/s12648-015-0756-y.