Journal of Radiation Research and Applied Sciences 8 (2015) 439–445

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Journal of Radiation Research and Applied Sciences

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Investigation of some radiation shielding parameters in soft tissue

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ARTICLE INFO

Article history:
Received 3 December 2014
Received in revised form
28 February 2015
Accepted 16 March 2015
Available online 30 March 2015

Keywords:
Energy absorption buildup factor
Soft tissue
Mass attenuation coefficient
Mass absorption coefficient
Effective atomic number

ABSTRACT

The photon interactions with the soft tissue have been discussed mainly in terms of mass attenuation coefficient, mass energy absorption coefficient, kerma relative to air, effective atomic number and energy absorption buildup factor in the energy range 0.01–10 MeV and penetration depth up to 40 mfp (by using GP fitting method). Over past 2 decades, interest has been growing for theoretical and computational works on photon buildup factor in soft tissue. Actually, besides dosimetry, in radiation therapy and imaging the buildup of X- and gamma photons introduces remarkable error.

1. Introduction

Since photons viz. gamma and X ray widely used in radiation therapy and medical imaging, the problem of flux deposition in the body and their biological effects is very important in shielding analysis. The mass attenuation coefficient, μ/ρ, and the mass energy–absorption coefficient, μ_{en}/ρ, are basic quantities used in calculations of the penetration and the energy deposition by photons (x-ray, γ-ray, bremsstrahlung) in biological, shielding and other materials (Hubbell & Seltzer, 1995).

On the other hand buildup factor is an important parameter in predicting and estimating the distribution of photon flux in irradiated object and calculation of radiation dose received by the biological molecules (Chilton, Shultis, & Faw, 1984; Sardari and Baradaran, 2010; Sardari, Abbaspour, Baradaran, Babapour, 2009). The buildup factors define in two terms: exposure in the air after penetration through the absorber or shielding material that called the "Exposure Buildup factor" (EBF). Other types of buildup factors also exist, in particular "Energy Absorption Buildup Factor" (EABF) for energy deposition in an absorbing medium and dose buildup factors in absorbing media (Martin, 2006).

Up till now, studies regarding EABFs in biological samples have been widely made using the well-known methods that is, geometric progression (GP) fitting method, generalized feed-forward neural network (GFFNN), and Monte Carlo N-

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Peer review under responsibility of The Egyptian Society of Radiation Sciences and Applications.
http://dx.doi.org/10.1016/j.jrras.2015.03.004

Particle (MCNP) codes (Harima, Sakamoto, Tanaka, & Kawai, 1986; Kucuk, Manohara, Hanagodimath, & Gerward, 2013; Kurudirek & Ozdemir, 2011; Manjunatha & Rudraswamy, 2011; Manohara, Hanagodimath, & Gerward, 2010; Manohara, Hanagodimath, & Gerward, 2011; Sidhu, Singh, & Mudahar, 1999, 2000; Mann & Sidhu, 2012; Mann, Kurudirek, Sidhu, 2012; Sardari et al., 2009).

Recently Sardari and Baradaran (2010) described a new relationship for estimating buildup factor as a function of penetration depth, Compton scattering, and energy absorption cross sections in water and soft tissue. In other work Sardari and Kurudirek developed this semi empirical equation approach to the data obtained through five parameter GP fitting method to the energy absorption buildup factor for soft tissue, water, and Hydrogen, Carbon, Nitrogen and Oxygen based some dosimetric materials (Sardari & Kurudirek, 2012). In this study some radiation shielding parameters such as the mass absorption coefficient, kerma relative to air, the equivalent atomic number and energy absorption buildup factors were investigated in the soft tissue.

2. Material and methods

2.1. Mass attenuation and absorption coefficients

The mass absorption coefficients of the soft tissue were determined using the transmission method according to Lambert–Beer's law ($I = I_0 \exp - \mu/\rho^* X$) where I_0 is the intensity of the incident beam, I(x) is the intensity after traversing a layer of material with mass-per-unit-area "X", and μ, the linear attenuation coefficient, is the probability of interaction per unit distance in an absorbing medium.

The mass attenuation coefficient ($\mu_m = \mu/\rho$) is of more fundamental importance than linear attenuation coefficient (μ) because all mass attenuation coefficients are independent of the density and physical state (gas, liquid or solid) of the absorber. This coefficient can be a useful coefficient because only the atomic composition of the attenuator is taken into account and not the individual density of the material (Hopkins, 2010).

The mass attenuation coefficient is a measure of the average number of interactions between incident photon and matter that occur in a given mass-per-unit area thickness of the material. It is distinguished sharply from the absorption coefficient which is always a smaller quantity and absorption coefficient measures the energy absorbed by the medium (Gupta & Sidhu, 2014).

Radiation exposure or absorbed dose of photons is determined by the amount of energy deposited by the various photon interactions as they traverse a medium such as tissue. Since some interactions produce radiant energy that carries energy out of the medium, the attenuation coefficient μ cannot be used to determine energy deposition in a medium. Consequently, a linear energy absorption coefficient μ_{en} has been defined that accounts for this loss:

$$\mu_{en} = \mu - (\text{scattering probability} + \text{other low probability interactions}) \quad (1)$$

Values of μ_{en} are based only on the energy absorbed into the medium; therefore, energy losses due to Compton-scattered photons, bremsstrahlung, and other radiative processes following interaction have been subtracted because they are very likely to leave the medium. The mass energy absorption coefficient μ_{en}/ρ with units of cm^2/g is the most useful form for determining radiation exposure or dose when a flux of x-rays or gamma rays is known or can be determined (Martin, 2006).

2.2. Effective atomic numbers

In order to define an effective atomic number (Z_{eff}) (Kurudirek, 2011; Sing & Badiger, 2014) in the soft tissue, we need to calculate two parameters:

1 The total electronic cross section (σ_e) for the individual element is calculated using the following equation:

$$\sigma_e = \frac{1}{N_A} \sum \frac{f_i A_i}{Z_i} \left(\frac{\mu}{\rho}\right)_{en} \quad (2)$$

where $f_i = n / \Sigma_i n_i$ denotes the fractional abundance of the element i with respect to the number of atoms such that $\sum_i^n f_i = 1$ is the atomic number of ith element.

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

$$\sigma_a = \frac{1}{N_A} \sum f_i A_i \left(\frac{\mu}{\rho}\right)_{en} \quad (3)$$

where μ_{en}/ρ is the mass energy absorption coefficient of the soft tissue, f_i is the fraction by weight of element i and A_i is the atomic weight of the element i.

The σ_e and σ_a are related to the effective atomic number, Z_{eff} of a composite material through the following relation.

$$Z_{eff} = \frac{\sigma_a}{\sigma_e} \quad (4)$$

The effective atomic numbers for the soft tissue were also calculated using Auto-Z_{eff} soft ware that collected in Table 1 (Taylor, Smith, Dossing, & Franich, 2012).

2.3. Kerma relative to air

Kerma of the soft tissue relative to air is defined as:

$$k_a = \frac{k_{\text{soft tissue}}}{k_{\text{Air}}} = \frac{(\mu_{en}/\rho)_{\text{soft tissue}}}{(\mu_{en}/\rho)_{\text{Air}}} \quad (5)$$

The mass energy absorption coefficient, μ_{en}/ρ for a mixture is calculated using:

$$(\mu/\rho)_{en} = \sum_i^n w_i (\mu_{en}/\rho)_i \quad (6)$$

where w_i and $(\mu_{en}/\rho)_i$ are the weight fraction and the mass energy absorption coefficient of the ith constituent elements present in the soft tissue. The values of (μ_{en}/ρ) have been taken from the literature (Martin, 2006; Sing & Badiger, 2014).

Table 1 – Linear attenuation coefficient (μ), mass attenuation coefficient (μ/ρ), and mass energy absorption coefficient (μ_{en}/ρ) coefficients for soft tissue.

E(MeV)	$\mu(cm^{-1})$	$\mu/\rho(cm^2/g)$	$\mu_{en}/\rho(cm^2/g)$	K_a	Z_{eff}
0.01	4.937	4.937	4.564	0.962463	6.196691
0.015	1.558	1.558	1.266	0.949025	6.119776
0.02	0.7616	0.7616	0.507	0.940805	5.916856
0.03	0.3604	0.3604	0.1438	0.935589	5.159014
0.04	0.2485	0.0683	0.2609	3.819912	4.433299
0.05	0.208	0.041	0.2223	5.421951	4.032305
0.06	0.1875	0.0304	0.2025	6.661184	3.807217
0.08	0.1662	0.0241	0.1813	7.522822	3.613184
0.1	0.1541	0.0233	0.1688	7.244635	3.536415
0.15	0.1356	0.025	0.149	5.96	3.474504
0.2	0.1233	0.0267	0.1356	5.078652	3.455224
0.3	0.1067	0.0287	0.1175	4.094077	3.442923
0.4	0.0955	0.0295	0.1051	3.562712	3.439475
0.5	0.0871	0.0297	0.0959	3.228956	3.437355
0.6	0.0806	0.0295	0.0887	3.00678	3.436119
0.8	0.0779	0.0779	0.0318	1.104167	3.435145
1	0.07	0.07	0.0307	1.100358	3.434995
1.5	0.057	0.057	0.0281	1.101961	3.435963
2	0.0489	0.0489	0.0258	1.097872	3.446637
3	0.0393	0.0393	0.0226	1.097087	3.477322
4	0.0337	0.0337	0.0204	1.090909	3.51639
5	0.03	0.03	0.0189	1.086207	3.558128
6	0.0274	0.0274	0.0179	1.084848	3.600351
10	0.0219	0.0219	0.0155	1.068966	3.759091

2.4. GP fitting method

The geometric progression (G-P) fitting formula is a theoretical method and is presented to determine the EABFs in most of the elements. This method has been developed by Harima (Sidhu et al., 2000b). The fitting parameters obtained by the GP formula and Taylor's formula are compiled in ANSI/ANS 6.4.3, (ANSI/ANS-6.4.3, 1991). To calculate the buildup factors, the G-P fitting parameters were obtained by the method of interpolation from the equivalent atomic number (Z_{eq}) (Kurudirek, Dogana, Ingeçb, Ekincia, & Özdemira, 2011; Salehi, Sardari, & Salehi Jozani, 2014). Computations are illustrated step by step as follows:

(a) Calculation of equivalent atomic number (Z_{eq}).

In the first step, the equivalent atomic number Z_{eq}, of a particular material was calculated by matching the ratio, $(\mu/\rho)_{Compton}/(\mu/\rho)_{total}$, of that material at a specific energy with the corresponding ratio of an element at the same energy. Thus, firstly the Compton partial mass attenuation coefficient $(\mu/\rho)_{Compton}$, and the total mass attenuation coefficients $(\mu/\rho)_{total}$, were obtained for soft tissue in the energy region 0.015–15 MeV, using the WinXCom computer program (Gerward, Guilbert, Jensen, & Levring, 2001, 2004) initially developed as XCOM (Berger & Hubbell, 1999).

For the interpolation of Z_{eq} for which the ratio $(\mu/\rho)_{Compton}/(\mu/\rho)_{total}$ lies between two successive ratios of elements, the value of Z_{eq} was calculated by using the following formula:

$$Z_{eq} = \frac{Z_1(\log R_2 - \log R) + Z_2(\log R - \log R_1)}{\log R_2 - \log R_1} \quad (7)$$

where Z_1 and Z_2 are the elemental atomic numbers corresponding to the ratios R_1 and R_2 respectively, and R is the ratio for the soft tissue at the specific energy. Z_{eq} at different energies are collected in Table 2.

The GP fitting parameters are calculated by logarithmic interpolation from the equivalent atomic number (Z_{eq}) of the soft tissue. So Z_{eq} is derived from the Compton scattering. The effective atomic number derived from the μ_{en}/ρ is a convenient parameter in dosimetry for representing the photon energy absorption in a complex medium (Kurudirek, 2011; Sidhu et al., 1999).

(b) Calculation of the geometric progression (GP) fitting parameters.

In the second step, to calculate the G-P fitting parameters, a similar interpolation procedure was adopted as in the case of equivalent atomic number. The G-P fitting parameters for elements were taken from the ANSI/ANS-6.4.3 (1991) standard reference database, which provides the G-P fitting parameters for elements, from beryllium to iron in the energy region 0.015–15 MeV up to a depth of 40 mean free path (or mfp, is the average distance that a particle travels between two consecutive collisions). G-P fitting buildup factor coefficients of the used materials were interpolated according to the given formula as follows:

$$P = \frac{P_1(\log Z_2 - \log Z_{eq}) + P_2(\log Z_{eq} - \log Z_1)}{\log Z_2 - \log Z_1} \quad (8)$$

where P is the G-P fitting function coefficient corresponding to Z_{eq}, P_1 and P_2 are the values of G-P fitting function coefficients corresponding to the element atomic numbers Z_1 and Z_2,

Table 2 – Energy absorption GP fitting parameters for soft tissue in the energy range 0.015 MeV–15 MeV.

E(MeV)	a	b	c	d	X_k	Z_{eq}
0.015	−0.012	3.514	1.099	−0.0016	13.45	7.28
0.02	−0.078	4.437	1.43	0.0304	13.61	7.31
0.03	−0.12	4.884	1.699	0.0527	13.71	7.33
0.04	−0.162	4.933	2.018	0.0725	13.61	7.33
0.05	−0.174	4.639	2.136	0.077	13.96	7.34
0.06	−0.176	3.869	2.173	0.0713	14.4	7.34
0.08	−0.175	3.365	2.146	0.0728	14.22	7.34
0.1	−0.161	2.884	1.997	0.0636	14.13	7.35
0.15	−0.146	2.642	1.86	0.0578	14.12	7.35
0.2	−0.134	2.474	1.756	0.0534	14.24	7.35
0.3	−0.121	2.366	1.662	0.0482	14.29	7.36
0.4	−0.101	2.211	1.526	0.0406	14.33	7.36
0.5	−0.086	2.105	1.428	0.0349	14.34	7.36
0.6	−0.06	1.935	1.276	0.0263	14.34	7.36
0.8	−0.039	1.839	1.172	0.0159	14.21	7.36
1	−0.012	1.711	1.054	0.0035	13.43	7.36
1.5	0.005	1.628	0.985	−0.0047	13.62	6.55
2	0.018	1.566	0.938	−0.0111	14.23	6.51
3	0.024	1.506	0.919	−0.017	14.89	6.51
4	0.037	1.43	0.876	−0.02	12.07	6.5
5	0.039	1.371	0.865	−0.0222	14.33	6.5
6	0.048	1.277	0.839	−0.034	15.44	6.5
8	−0.012	3.514	1.099	−0.0016	13.45	6.49
10	−0.078	4.437	1.43	0.0304	13.61	6.49
15	−0.12	4.884	1.699	0.0527	13.71	6.4

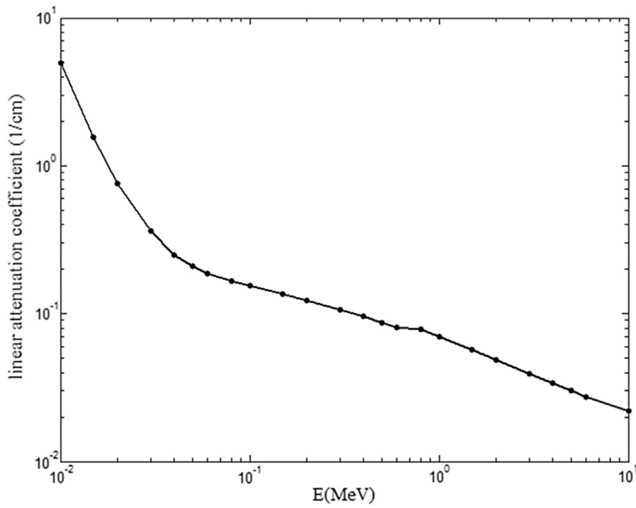

Fig. 1 – Variation of linear attenuation coefficients with photon energy for soft tissue in the energy range 0.01–10 MeV.

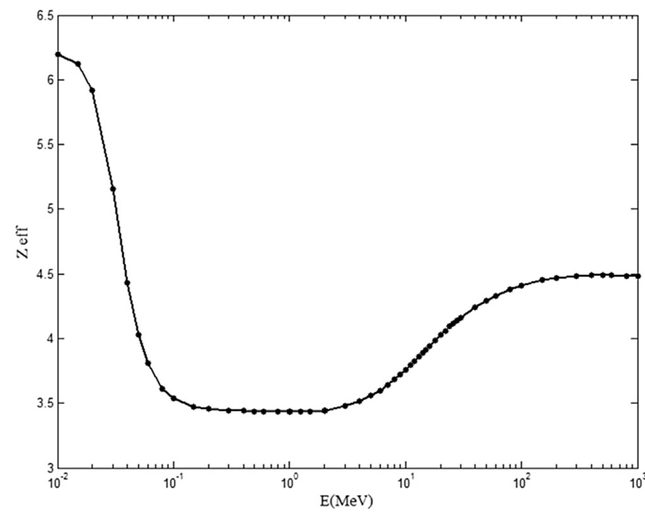

Fig. 3 – Variation of effective atomic numbers with photon energy for soft tissue in the energy range 0.01–10 MeV.

respectively, at a given energy, whereas Z_{eq} is the equivalent atomic number of the chosen material at the given energy.

(c) Calculation of the EABF:

In the final step, the computed G-P fitting parameters (b, c, a, X_k and d) are used to compute the EABFs of soft tissue in the energies 0.015–15 MeV and penetration depths up to 40 mfp with the help of the G-P fitting formula, as given by the equations (Harima et al., 1986):

$$B(E,x) = 1 + \frac{(b-1)(K^X - 1)}{K-1} \quad \text{For } K \neq 1 \tag{9}$$

$$B(E,x) = 1 + (b-1)x \quad \text{For } K = 1 \tag{10}$$

where

$$K(E,x) = cx^a + d\frac{\tanh(x/X_k - 2) - \tanh(-2)}{1 - \tanh(-2)} \quad \text{For } (x) \leq 40 \text{ mfp} \tag{11}$$

and E is the incident photon energy, x is the penetration depth in mfp, a, b, c, d and X_k are the G-P fitting parameters and b is the value of the buildup factor at 1 mfp. The parameter K represents photon dose multiplication and a change in the shape of the spectrum. GP fitting parameters for the EABF (b, c, a, X k and d) of soft tissue are shown in Table 2 (Manohara et al., 2011).

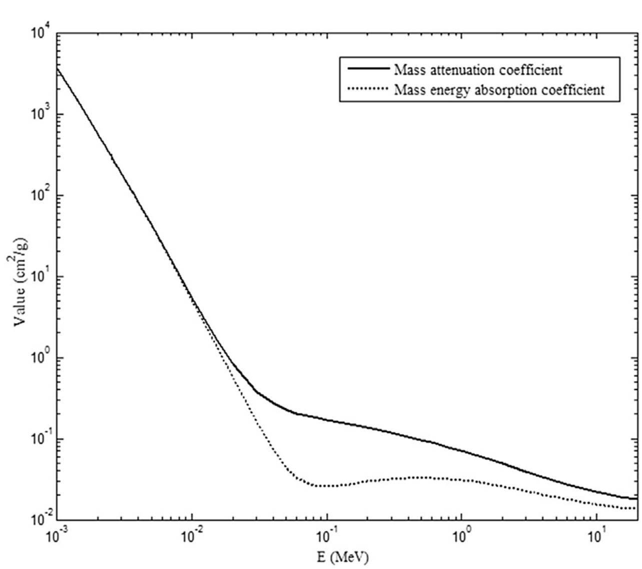

Fig. 2 – Variation of mass energy attenuation and absorption coefficient with photon energy for soft tissue in the energy range 0.01–10 MeV.

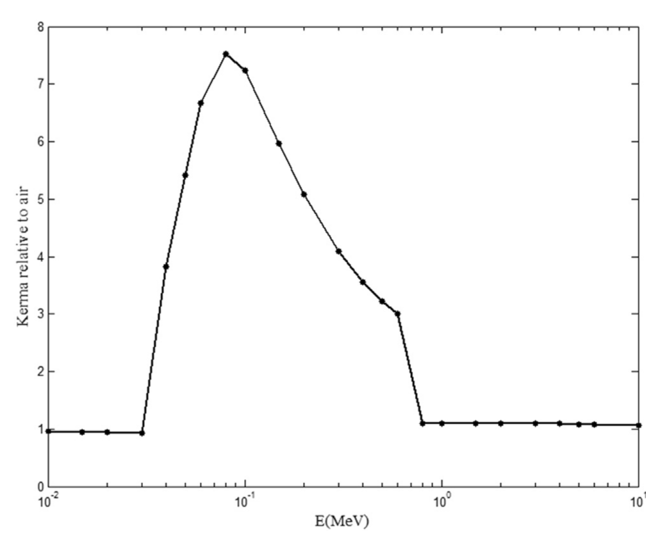

Fig. 4 – Variation of Kerma relative to air with photon energy for soft tissue in the energy range 0.01–10 MeV.

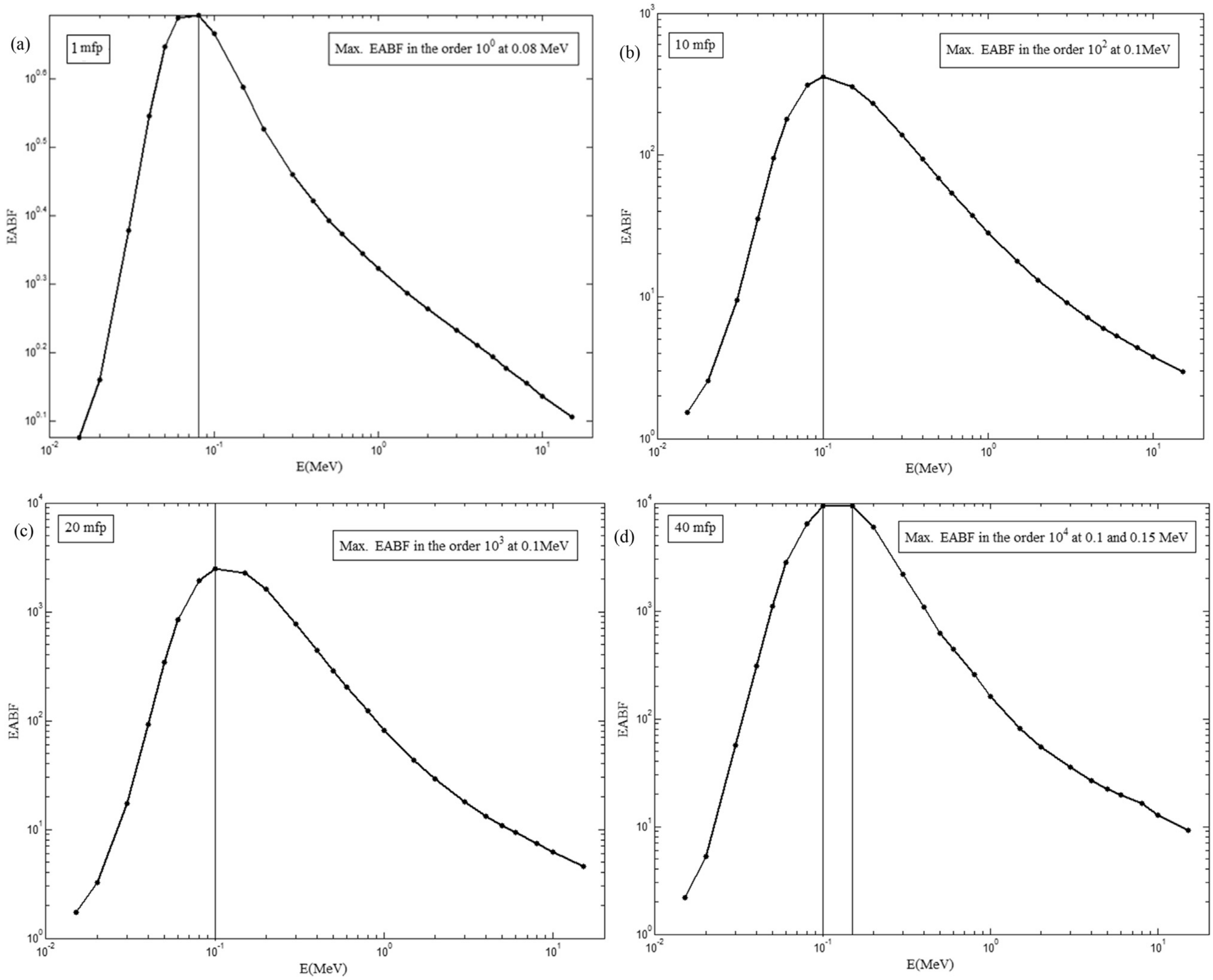

Fig. 5 – Variation of the energy absorption buildup factor with photon energy for soft tissue in the energy region 0.015–15 MeV at (a) 1, (b) 10, (c) 20 and (d) 40 mfp.

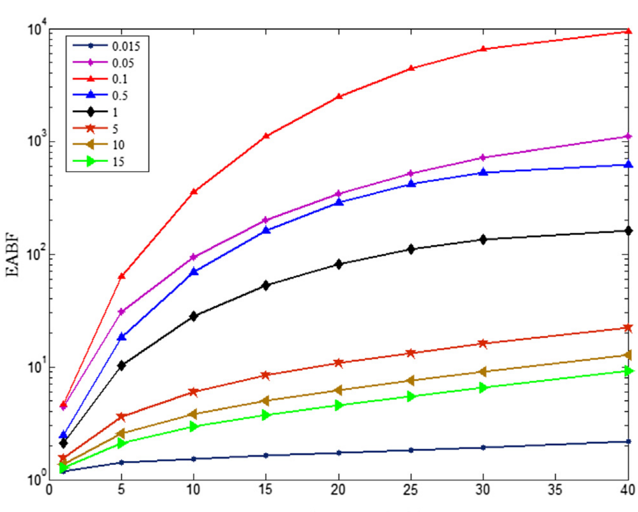

Fig. 6 – The energy absorption buildup factor for soft tissue up to 40 mfp at 0.05–15 MeV.

3. Results and discussion

3.1. *Variation of radiation shielding parameter with energy in soft tissue*

Values of μ_{en}/ρ are provided along with values of μ, μ/ρ and Z_{eff} in Table 1 in soft tissue for determination of radiation exposure in air and radiation dose in tissue. Variations of the mass absorption and attenuation coefficients and the linear attenuation coefficients, effective atomic numbers and Kerma of the soft tissue relative to air with incident photon energy are shown in Figs. 1–4 (Hubbell & Seltzer, 1995). Since the electronic cross section of elements for Compton scattering is constant, μ/ρ and μ_{en}/ρ are approximately the same for elements as well as compounds in intermediate energy region where Compton scattering is the pre-dominant interaction process (Kurudirek, 2011). Thus, in this energy region μ/ρ and μ_{en}/ρ values of the soft tissue vary only with respect to the photon energy.

It is observed that μ_m of soft tissue is initially high and decreases sharply with the increase in incident photon energy up to 0.06 MeV. In the incident photon energy region above 0.06 MeV–1 MeV the μ_m of selected materials have almost same. Above 1 MeV, there is again a slight variation in μ_m with incident photon energy because in this energy region pair-production process dominance. There is a same behavior for μ_{en}/ρ values, so that in $E \le 0.08$ MeV, μ_{en}/ρ decreases sharply with the increase in incident photon energy at 0.3 MeV has been seen a little rise in the values of μ_{en}/ρ up 0.5 MeV. Above 0.5 MeV, there is again a slight variation in μ_{en}/ρ with incident photon energy.

From the results it is observed that at lower energies (0.015–0.8 MeV), the effective atomic number shows a markedly decreasing trend. This behavior can be explained on the basis that, in the lower-energy region, the photoelectric absorption is the most dominant process. So for a particular value of incident photon energy, as one move from the lower to the higher Z_{eff} values, the photons are more readily absorbed by photoelectric interaction, so their lifetime in the soft tissue is small.

For incident photon energies 0.015–3 MeV there is almost no change in the value of Z_{eff} in soft tissue; this confirms the fact that the chemical composition materials does not affect their attenuation properties at intermediate energies. For incident photon energy 4 MeV up 100 MeV the equivalent atomic number began to increase (Sidhu et al., 2000b).

Our results show at 0.01 MeV the values of linear attenuation coefficients and mass energy absorption coefficient are the maximum for soft tissue. It is found that the K_a values of the soft tissue reach unity in the energy region 0.01–0.03 MeV and in 0.04–0.4 MeV is the maximum, so that there is a peak at 0.08 MeV and in 0.8–10 MeV the K_a value is approximate unite.

3.2. *Variation of EABF with energy and penetration depths*

The variation of the EABF with incident photon energy is shown in Fig. 5. It can be seen EABF has low values at lower and higher energies. This is due to the dominance of photoelectric absorption and pair production, which result in the complete removal of photons. The maximum values of EABF were observed at intermediate energies, where Compton scattering dominates. In this process, the photons are not completely removed but only their energies are degraded. Besides, their directions are changed. Hence, this process results in more multiple scattered photons, which leads to increase in the buildup of photons in the medium.

EABF increases with increasing penetration depth; these various complexities are illustrated in Fig. 6. It has been shown that with increasing penetration depths, EABF also increase due to increase in number of scattered photons. The maximum values of the EABF in soft tissue, which are in the order of 10^4, have been obtained at the largest penetration depth (40 mfp) and in 0.1 MeV.

4. Conclusion

Knowledge of radiation interaction with tissue is also of importance for researchers working in radiological laboratories, reactors and nuclear power plants to take proper precautions to avoid radiation hazards. Also, by determining the elemental composition of different tissues, new tissue substitute phantom materials can be developed, which will further be used in experiments where measurements are made under radiation conditions. In this work some radiation shielding parameters such as mass attenuation coefficient, mass energy absorption coefficient, kerma relative to air, effective atomic numbers investigated in soft tissue and energy absorption buildup factor were calculated for soft tissue. The mass energy absorption coefficient μ_{en}/ρ is the most useful form for determining radiation exposure when a flux of x-rays or gamma rays is known or can be determined.

Acknowledgement

This research work has partly been accomplished at Science and Research Branch, Islamic Azad University, Tehran, Iran.

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