PHOTON BUILDUP FACTORS FOR SOME TISSUES AND PHANTOM MATERIALS FOR PENETRATION DEPTHS UP TO 100 MFP

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Abstract

The use of photons in diagnostic and therapeutic medicine requires the accurate determination of photon irradiation dose in human tissues. Photon buildup factors represent corrections to photon interaction when the Beer-Lambert conditions are not met. Equivalent atomic numbers, energy absorption and exposure buildup factors of 10 human tissues (adipose tissue, blood, collar bone, brain, breast, eye lens, lungs, ovary, testis and skeletal muscles) and 4 equivalent materials (water, nylon, mylar and polyvinylchloride) were evaluated using the geometric progression (G-P) fitting method. The buildup factors were evaluated for 25 standard photon energies (0.015-15 MeV) and for penetration depth up 100 mfp (mean free path). The magnitudes equivalent atomic numbers and buildup factors for the studied materials varied in similar pattern with energy and penetration depth. The variations in the equivalent atomic number and the buildup factors with photon energy were attributed to elemental compositions of the individual tissue/ equivalent material and the dominance of different photon interaction in the energy spectrum considered. The behaviour of the equivalent atomic number for the equivalent materials suggests that each of them can be used to represent different human tissues for phantom construction and dose evaluation.

Keywords: *Phantom, Photons, G-P Fitting parameters, Human tissues, Buildup factors*

Introduction

X- and gamma-rays are both used in medicine for diagnostic (radiography, mammography, nuclear medicine etc.) and therapeutic (radiotherapy and radio surgery) procedures [1]. In these applications, an uncontrolled exposure of human tissues to photons depending on the energy of the radiation and exposed tissues among other factors could lead to further clinical symptoms. Adequate knowledge of photon interaction with human tissues and organs is thus required in order to control radiation exposure as this will indicate how much energy of the radiation is deposited in the tissues.

In radiation physics, interaction of ionising radiation with human tissues and consequent radiation dose are sometimes simulated by the use of tissue equivalent materials (phantom). To qualify as equivalent material for human tissue, a phantom should not only have similar elemental composition as that of the tissue it represents, it should also respond to photons the same way as the tissue.

The linear attenuation coefficient is a fundamental parameter describing photon interaction with matter. It is also a quantity that describes how much photon is absorbed, transmitted or scattered by a medium. Generally, the transmission of photon through a material is estimated by the Lambert-Beer law [2]:

$$I = I_0 e^{-\mu t} \qquad (1)$$

where the incident photon intensity $I_{o,}$ is reduced to I after passing through a shield material of thickness t and linear attenuation coefficient μ.

However, Lambert-Beer law assumes monochromatic rays, thin absorbing material, and narrow beam geometry. Any deviation from the mentioned assumptions requires the Lambert-Beer law to be modified to account for multiple scattering of photons in the following form [3]:

$$I = B \cdot I_0 e^{-\mu t} \qquad (2)$$

where the correction factor B is referred to as the buildup factor. B is always greater than 1 where the Lambert-Beer assumption does not apply; otherwise it is equal to unity.

B accounts for the ratio of broad beam to that of narrow beam and directly influences radiation dose. Two types of buildup factors are recognised: (i) the energy absorption build up factor (EABF) in which the quantity of interest is the absorbed or deposited energy in the interacting medium and the detector response function is that of absorption in the interacting medium; (ii) the exposure buildup factor (EBF) in which the quantity of interest is the exposure and the detector response function is that of absorption in air [4].

The buildup factor is a function of photon energy and penetration depth. The penetration depth is however always expressed in terms of a dimensionless quantity,

(μt) called the mean free path (mfp). The mean free path refers to the average distance between two successive photon interactions in a medium in which the photon propagates such that the intensity of the beam is reduced by a factor *1/e.*

The American Nuclear Society [5] has compiled photon point isotropic source data for both EABF and EBF for 23 elements (Be, B, C, N, O, Na, Mg, Al, Si, P, S, Ar, K, Ca, Fe, Cu, Mo, Sn, La, Gd, W, Pb and U), one compound (water) and two mixtures (air and concrete), for standard photon energies in the range 0.015 MeV - 15 MeV, and penetration depth up to 40 mean free path (mfp).

Furthermore, B has been evaluated for different types of materials (not included in above mentioned ANS report) by many researchers using various computer codes (such as: PALLAS [6], ASFIT [7], and EGS4 [8-10]) and different computational methods (Iterative method [11], Geometric progression Fitting (GP) [12], Monte Carlo method [13], Invariant embedding [14], Generalised Feed Neural Network (GFFN) [15], etc). Evaluated buildup factors in the literature do not normally exceed penetration depth of 40 mfp. However, sometimes during the treatment of deep seated tumour this depth may be exceeded. Consequently, the data corresponding to mfp beyond 40 are needed.

Generally, for shielding and dosimetry purpose, accurate and reliable data on buildup factors have great importance. Consequently, the computed EBF and EABF data of ten tissues (such as: adipose tissue (ADT), blood (BLD), collar bone (CLB), brain (BRN), breast (BRT), eye lens (ELS), lungs tissue (LST), skeletal muscle (SMS), ovary (OVY), and testis (TST)), and four equivalent materials (water, nylon (NYL), mylar (MYL), and polyvinylchloride (PVC)), for photon energies in the range 0.015 MeV – 15 MeV and penetration depth up to 100 mfp, are generated and present in the paper using G-P fitting approximation. The dependency of the buildup factors on the equivalent atomic number (Z_{eq}), energy and penetration depth is also discussed. Data obtained in this paper are useful for the accurate determination of energy deposited in tissue at different depth and could also assist in the choice of good tissue equivalent material.

Computational method

The 14 composite materials (4 phantom and 10 tissues) considered in this work and their elemental constituents (%) are presented in Table 1. The chemical composition of the materials was obtained from the literature [16-18].

Equivalent atomic number (Z_{eq}), G-P fitting parameters, energy absorption buildup factor (EABF) and exposure buildup factor (EBF) corresponding to the considered phantom/human tissues were evaluated for 25 standard photon energies (0.015 MeV – 15 MeV). However, the EBF and EABF were estimated up to photon penetration depth of 100 mfp. The computation of these parameters was done in three distinct stages: (i) calculation of equivalent atomic number, Z_{eq}; (ii) evaluation of GP fitting parameters; (iii) estimation of EABF and EBF for all considered tissue and phantom materials.

Table 1. Elemental composition (%) of the considered phantom/tissue materials [16-18]

Phantom/Tissue	Elemental Composition (%)											
	H	C	N	O	Na	Mg	P	S	Cl	K	Ca	Fe
Nylon (NYL)	11.3	62.61	12.17	13.91								
Mylar (MYL)	6.06	45.45		48.48								
Water	11.11			88.89								
Polyvinylchloride (PVC)	5.31	31.86							62.83			
Adipose tissue (ADT)	11.4	59.8	0.7	27.8	0.1			0.1	0.1			
Blood (BLD)	10.2	11.0	3.3	74.5	0.1		0.1	0.2	0.3	0.2		0.2
Collar bone (CLB)	3.40	15.5	4.2	43.5	0.1	0.2	10.3	0.3			22.5	
Brain (BRN)	10.7	14.5	2.2	71.2	0.2		0.4	0.2	0.3	0.3		
Breast (BRT)	10.6	33.2	3.0	52.7	0.1		0.1	0.2	0.1			
Eye lens (ELS)	9.6	19.5	5.7	64.6	0.1		0.1	0.3	0.1			
Lungs tissue (LST)	10.3	10.5	3.1	74.9	0.2		0.2	0.3	0.3	0.2		
Skeletal muscle (SMS)	10.2	14.3	3.4	71.0	0.1		0.2	0.3	0.1	0.4		
Ovary (OVY)	10.5	9.3	2.4	76.8	0.2		0.2	0.2	0.2	0.2		
Testis (TST)	10.6	9.9	2.0	76.6	0.2		0.1	0.2	0.2	0.2		

Calculation of Effective Atomic Number (Z_{eq})

The scattering and absorption of photons in any material, at a particular energy, is described by the photoelectric effect, the Compton scattering, and the pair production coefficients [18]. All of these three interaction modes of photons depend on the atomic number of the interacting medium. The Z_{eq} of a composite material is synonymous to the atomic number of an element. It describes the properties of the material as the atomic number describes the properties of an element with respect to radiation interaction. It represents a weighted average of the electron per atom in a multi-element material.

To evaluate Z_{eq} of the 14 composite materials considered in this study, their Compton partial interaction coefficient (μ_c) and mass attenuation coefficients (μ_T) (both given in cm^2/g) were calculated for the photon energy range from 0.015 MeV to 15 MeV using the WinXCom computer code [19], initially developed as XCom by Berger and Hubbel [20].

The ratio $R = \mu_c/\mu_T$ of each material is then obtained and matched at the standard energies to the corresponding ratio of elements up to the heaviest element in composite materials. However, the value of R for all tissue and phantom materials considered in the study did not matched that of any element, but rather fell between ratios of two successive elements. Consequently, their Z_{eq} have been interpolated using the expression [2, 4]:

$$Z_{eq} = \frac{Z_1\left(\log R_2 - \log R\right) + Z_2\left(\log R - \log R_1\right)}{\log R_2 - \log R_1} \quad (3)$$

R_1 and R_2 are the ratios (μ_c/μ_T) of the two successive elements of atomic numbers Z_1 and Z_2, respectively, within which R falls at corresponding energies.

The evaluation of photon buildup factors by means of the G-P fitting method requires 5 fitting parameters. These coefficients (b, c, a, X_k, and d) depend on Z_{eq} and photon energy. ANS report [5] has provided these coefficients for 23 elements and for 25 standard photon energies. However, since the (μ_c/μ_T) for the materials considered in the present study did not match any of the 23 elements, their G-P fitting coefficients were also interpolated using the logarithmic interpolation formula given below:

$$F = \frac{F_1\left(\log Z_2 - \log Z_{eq}\right) + F_2\left(\log Z_{eq} - \log Z_1\right)}{\log Z_2 - \log Z_1} \quad (4)$$

where F_1 and F_2 are the values of G-P fitting parameters obtained from ANS data base corresponding to the atomic numbers Z_1 and Z_2, respectively.

Evaluation of Buildup factors

The buildup factors (EABF and EBF) were estimated for the considered energy spectrum for different penetration depth up to 100 mfp by using the equations [2, 12, 21, 22] given in the following:

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

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

where

$$K(E,x) = cx^a + d\,\frac{\tanh\left(\frac{x}{X_K} - 2\right) - \tanh(-2)}{1 - \tanh(-2)} \quad (7)$$

for $x \leq 40$ mfp

For penetration depth greater than 40 mfp the following expressions are used instead of Eq.(7):

$$K(E,x) = 1 + (K_{35} - 1)\Phi, \text{ for } 0 \leq \Phi \leq 1 \quad (8)$$

$$K(E,x) = K_{35}\left(\frac{K_{40}}{K_{35}}\right)^{\in(x) f}, \text{ for } \Phi < 0, \Phi > 1 \quad (9)$$

$$\in(x) = \frac{\left(x/35\right)^{0.1} - 1}{\left(40/35\right)^{0.1} - 1}, \quad f = 0.8 \quad (10)$$

$$\Phi = \frac{K_{40} - 1}{K_{35} - 1} \quad (11)$$

$$K_{35} = K(E, 35) \quad \text{and} \quad K_{40} = K(E, 40) \quad (12)$$

The factor $K(E, x)$ is the photon dose multiplier factor at energy E, and depth x (mfp). It represents the change in shape of the spectrum from that of 1 mfp. Eqs. (5, 6) and (8-12) were used to calculate the exposure buildup factor (EBF) and the energy absorption buildup factor (EABF) for 25 standard photon energies and the 14 materials under investigation.

Results and discussions

Equivalent Atomic Number (Z_{eq}) and dependence on photon energy

The calculated Z_{eq} for all the tissue and phantom materials considered in the study, and their dependence on photon energy (0.015 MeV- 15 MeV) is presented in Figure 1. Z_{eq} of the materials vary similarly with respect to photon energy-increased slightly in the low energy region up to 1 MeV and subsequently dropped as energy increased up to 2 MeV. Beyond this energy, the materials' Z_{eq} values were almost constant throughout the remaining part of the energy spectrum.

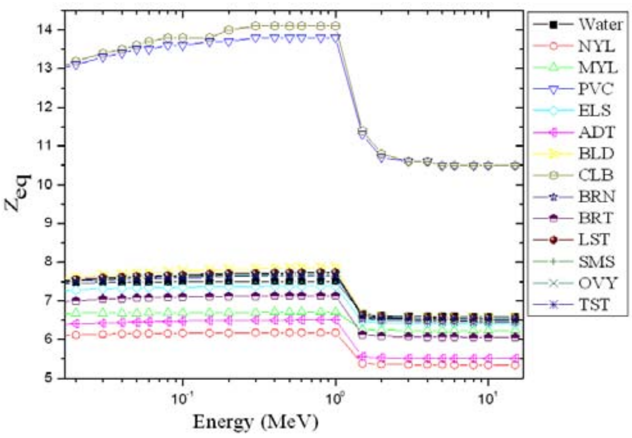

Fig. 1. Equivalent atomic number of considered tissues and phantom materials

The magnitude and variation of Z_{eq} for the tissues and phantom materials considered in the study could be attributed to their chemical compositions and photon interaction. Consequently, tissues containing high atomic number elements have comparatively high Z_{eq} and vice versa. For each material, the upper and lower boundary of the equivalent atomic number was dictated by the minimum and maximum atomic number in its composition [18]. This explains why PVC and CLB have the highest Z_{eq} as they both contain about 63% of Cl and 23% of Ca respectively. These two elements have relatively high atomic numbers and abundance in the two materials comparatively to other chemical constituents in the other tissues and phantoms.

Z_{eq} of the materials under study could be grouped into three categories depending on the range of values: low (Z_{eq} between 5 and 7), intermediate (Z_{eq} between 7 and 8) and high (Z_{eq} between 10 and 13). For photon energies below 1 MeV the low, intermediate and high Z_{eq} materials are, as follows: low - MYL, ADP and NYL; intermediate - Water, ELS, BLD, BRN, BRT, LTS, SMC, OVY and TSL; high - PVC and CLB.

Beyond 1 MeV, both MYL and ADP remained in the low Z_{eq} materials and have values very close one to the other. The closeness in materials' Z_{eq} suggests that MYL can be used as a substitute/phantom material for adipose tissue. Furthermore, NYL joins other intermediate Z_{eq} materials in the high energy region with all of them having equivalent atomic numbers between 6 and 7. The values of Z_{eq} of PVC and CLB also dropped to about 11 in the energy region beyond 1 MeV. The almost equal equivalent atomic numbers of PVC and CLB, and the similarity in their variation with photon energy is an indication that PVC can be a good substitute material for CLB in the energy region under investigation.

Buildup factors

The evaluated buildup factors of any material using the G-P fitting procedure depends on the photon energy, the penetration depth and its fitting parameters (a, b, c, d, and X_k) according to Eqs. (3-5). On the other hand, the G-P coefficients are dictated by the chemical constituents of the materials. Consequently, Z_{eq}, which is a parameter that depends on elemental composition of a material, would influence, to a large extent, the magnitude of energy absorption and exposure buildup factors in the material. It is thus appropriate to suggest that the energy of photon, the penetration depth and Z_{eq} of a material are the major indices influencing photon buildup factor in the material.

The photon energy range in which the buildup factors were estimated for the present study corresponds to that where photoelectric effect, Compton scattering and pair production are the main photon interaction modes. These three modes of interaction are important for the energy deposition of photons in any medium [18]. Furthermore, the photoelectric effect (τ), the Compton scattering (σ), and the pair production (κ) coefficients are all independently related to the photon energy and the atomic number (Z) of an interacting medium according to the following approximation equations [23]:

$$\tau = p\frac{Z^5}{E^3} \quad (13)$$

$$\sigma = q\frac{Z}{E} \quad (14)$$

$$\kappa = rZ^2\left(E-1.022\right) \quad (15)$$

where p, q, and r are constants. For a composite material such as those considered in this study, Z_{eq} can be used as a good approximation for Z in Eqs. (13-15). Thus, considering the dominance of any of these interaction modes, Z_{eq} and photon energy are responsible for the buildup factors variations at different penetration depths.

Variation of EABFand EBF with photon energy

Considering 25 standard photon energies in the energy range 0.015 Mev-15 MeV and penetration depths up to 100 mfp, EABF and EBF variations for all 14 materials under investigation are depicted in the following figures.

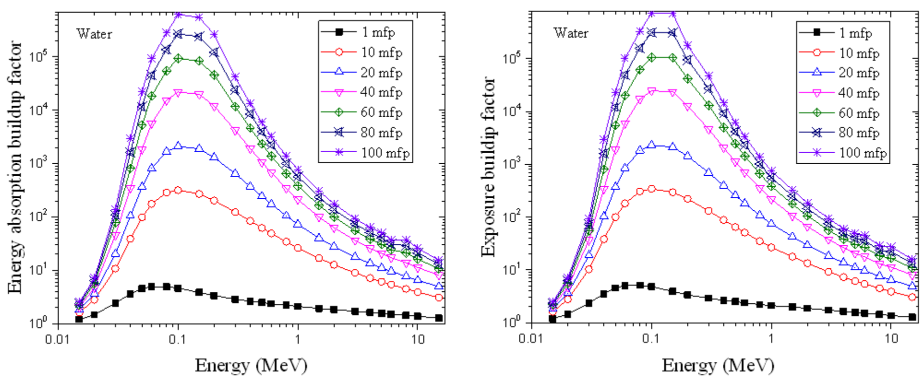

Fig. 2. Energy Dependence of energy and exposure buildup factors for water

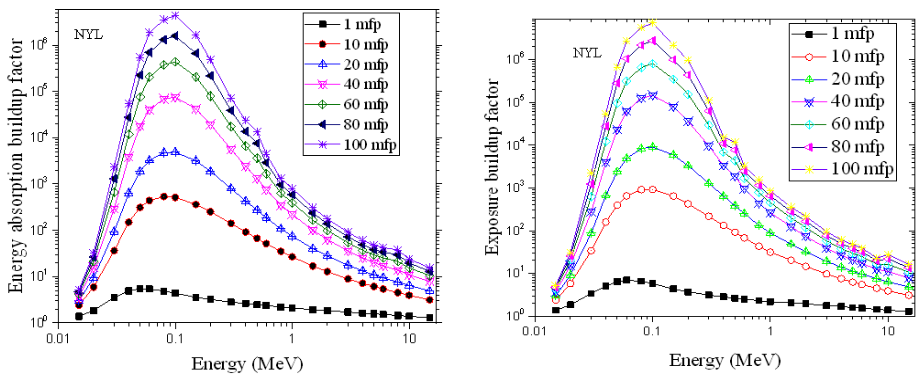

Fig. 3. Energy Dependence of energy and exposure buildup factors for NYL

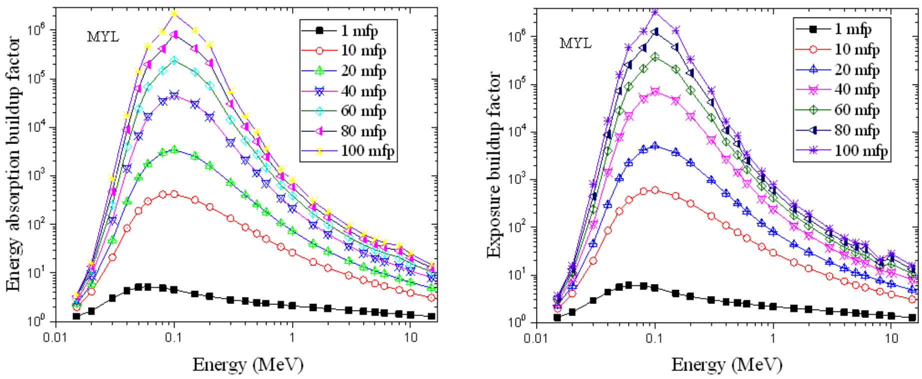

Fig. 4. Energy Dependence of energy and exposure buildup factors for MYL

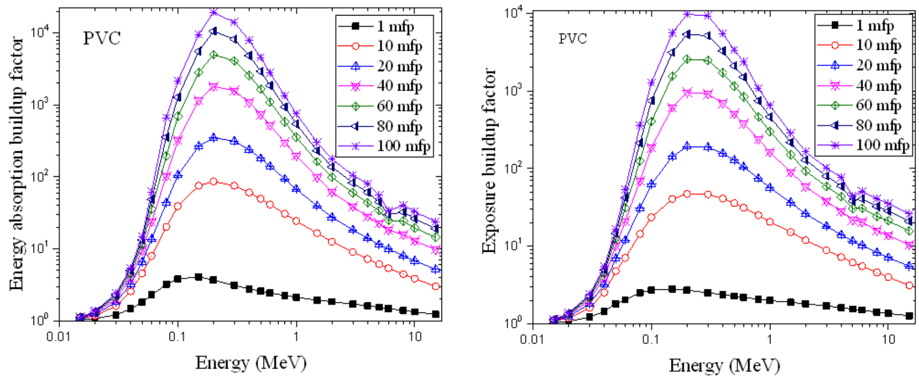

Fig. 5. Energy Dependence of energy and exposure buildup factors for PVC

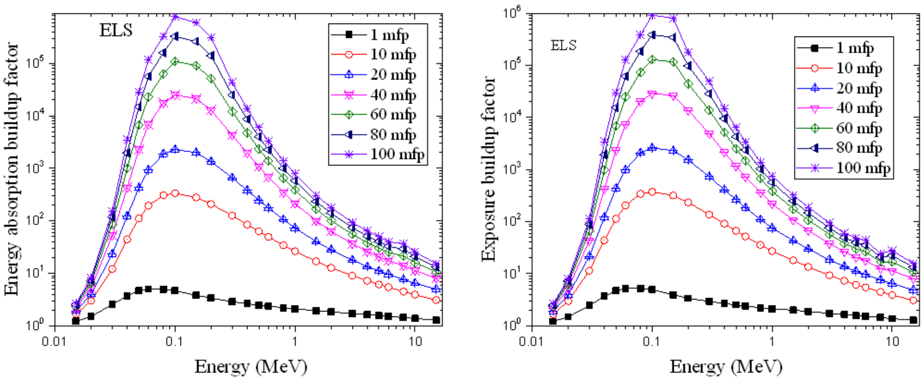

Fig. 6. Energy Dependence of energy and exposure buildup factors for ELS

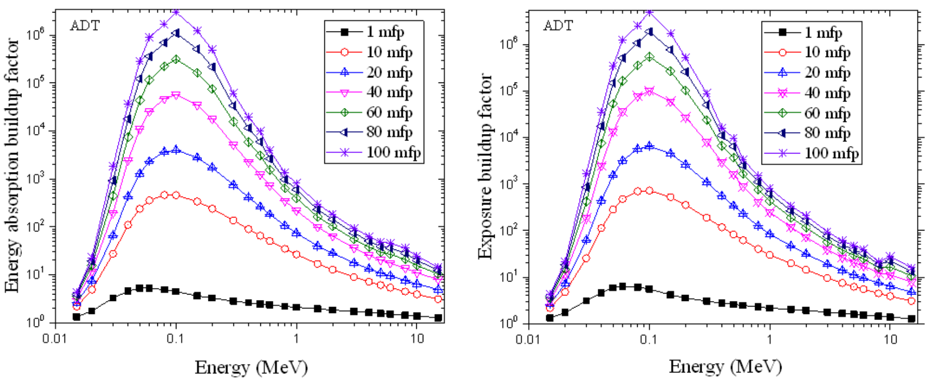

Fig. 7. Energy Dependence of energy and exposure buildup factors for ADT

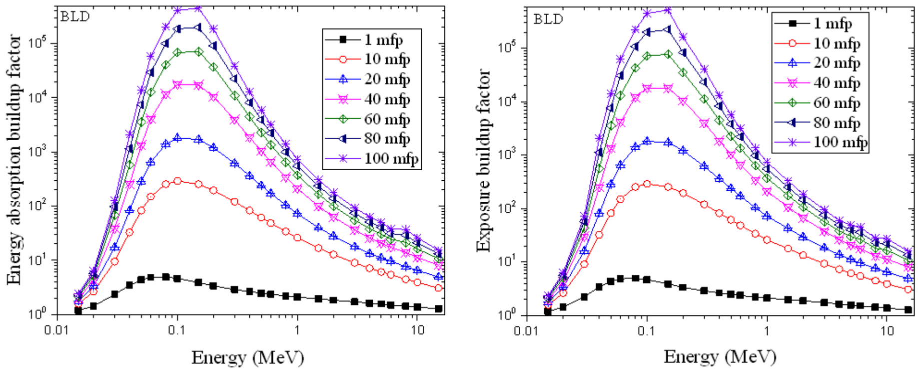

Fig. 8. Energy Dependence of energy and exposure buildup factors for BLD

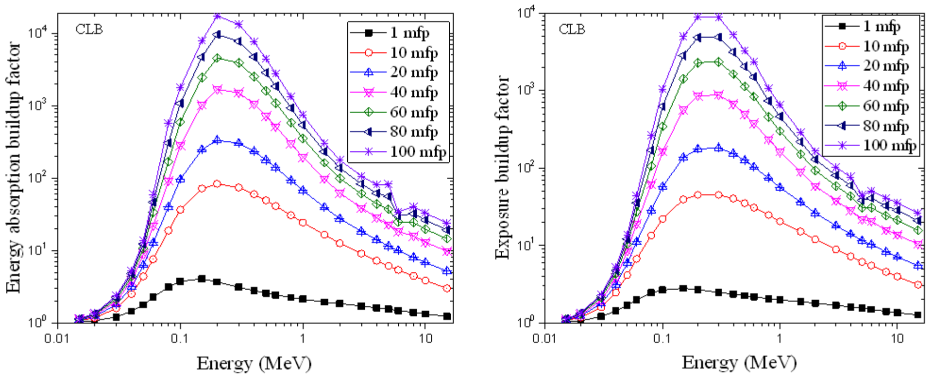

Fig. 9. Energy Dependence of energy and exposure buildup factors for CLB

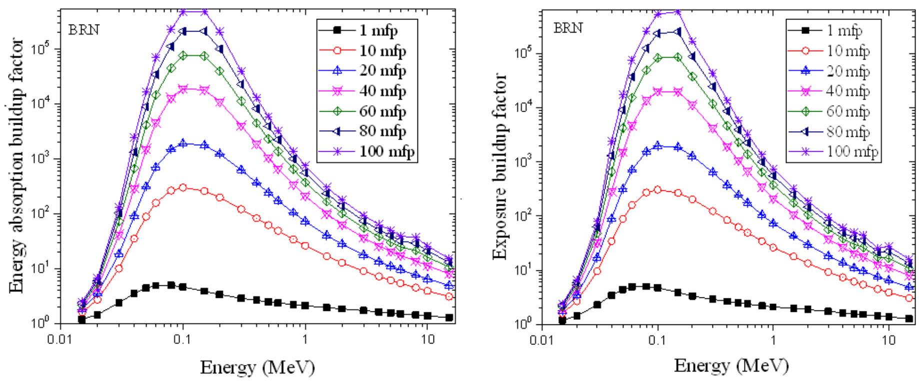

Fig. 10. Energy Dependence of energy and exposure buildup factors for BRN

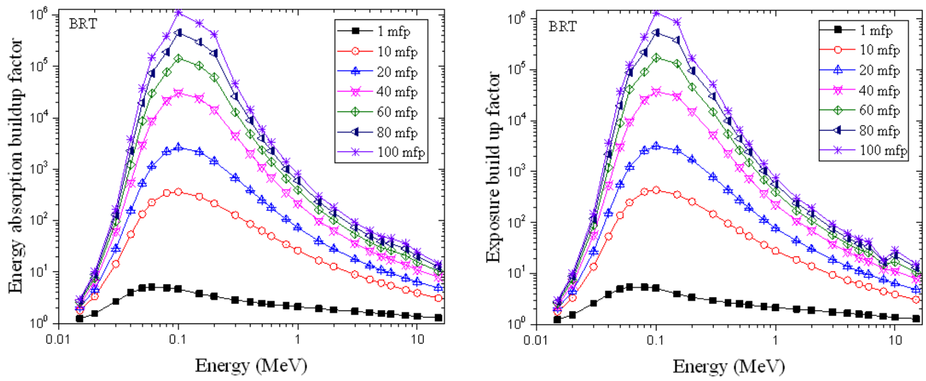

Fig. 11. Energy Dependence of energy and exposure buildup factors for BRT

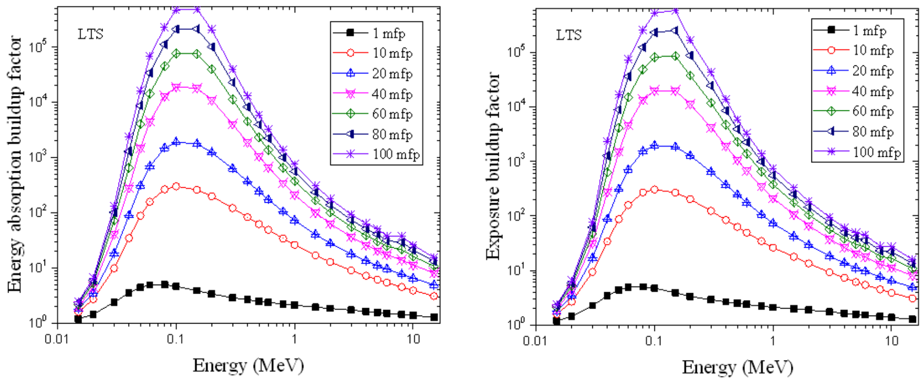

Fig. 12. Energy Dependence of energy and exposure buildup factors for LTS

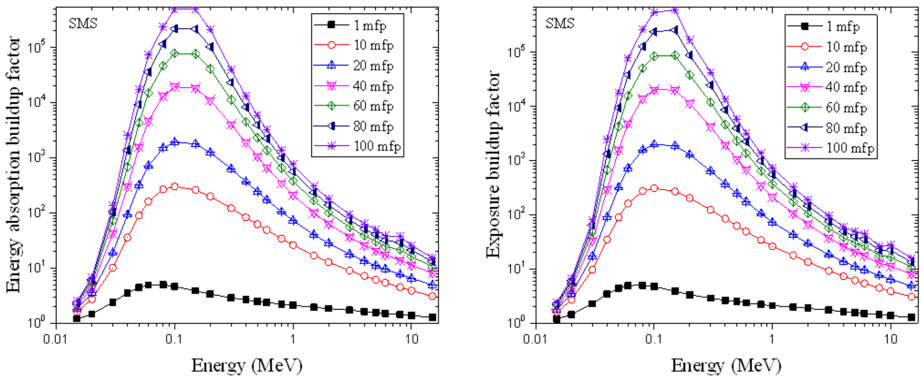

Fig. 13. Energy Dependence of energy and exposure buildup factors for SMS

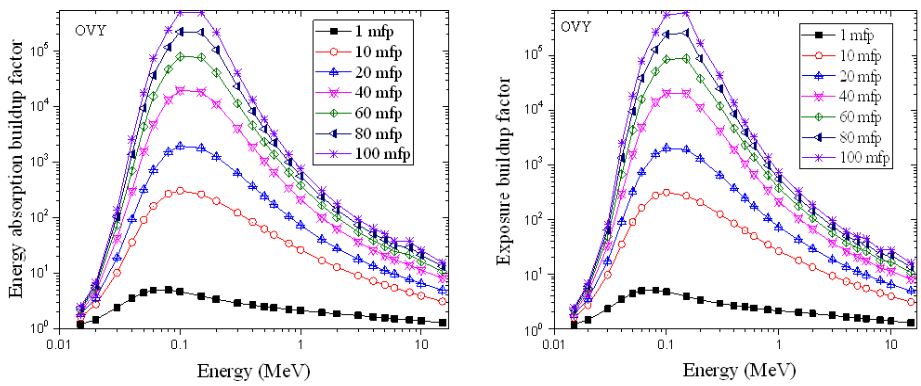

Fig. 14. Energy Dependence of energy and exposure buildup factors for OVY

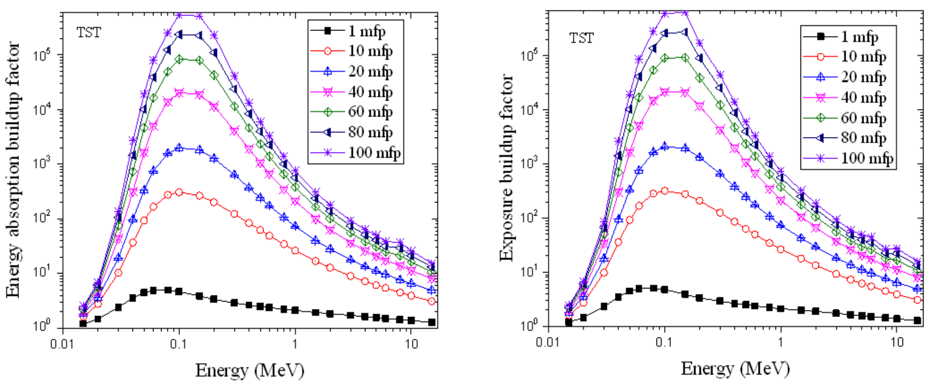

Fig. 15. Energy Dependence of energy and exposure buildup factors for TST

As it can be seen in Figures (2-15), the changes in buildup factors with energy are similar regardless the material type and depth of interaction. Generally, the buildup factors are low and become greater with increasing in energy up to they reach a maximum value. The position of this peak varies slightly and depends on penetration depth and material type. However, most of the buildup factors peaks fall between 0.1 MeV and 0.3 MeV. Beyond the peak energy, the photon buildup of all the tissue and phantom materials decreases rapidly with increasing of the photon energy, regardless the penetration depth. This behaviour of the buildup factors can be attributed to the different photon interaction modes dominating at different photon energies. The entire energy spectrum can be divided into three distinct regions: low (0.015 – 0.03 MeV); intermediate (0.03- 1 MeV); and high (1-15 MeV) energy regions. In each of these energy regions, one of the three photon interaction modes, whose coefficients are represented by Eqs. (13-15), dominates and, consequently, dictates the EABF and EBF magnitude.

In the lower energy region, the photoelectric effect is the principal mode of photon interaction. In this region, buildup factors are generally low and vary inversely as the Z_{eq} increase. This is due to the fact that the photoelectric process removes the photon completely from the beam thus preventing photon buildup. According to Eq. (13), the probability of photoelectric effect to take place is directly proportional to the atomic number of the material. Hence, high Z_{eq} materials have a higher potential to remove completely more photons than low Z_{eq} materials. This accounts for the lower buildup of photons in the high Z_{eq} tissues and phantom materials at the low energy region. As the photon energy increases, the influence of the photoelectric effect diminishes. The Compton interaction mode, whose coefficient is given by Eq. (14), dominates at the intermediate photon energies. The buildup factors are very high due to the fact that Compton scattering does not completely remove photons from the beam, but rather degrades the photons as a result of multiple scatterings. In the energy region beyond 1.02 MeV (high energy region), the pair production become the main mode of photon interaction. The pair production mode removes completely photons from the beam after interaction, thus preventing the buildup. Consequently, the buildup factors in the high energies region are also very low.

Buildup factors and the penetration depth

Several energies from the considered photon energy range have been selected, and the variation of the absorption buildup factor with the penetration depth is presented in Figure 16, for the 14 materials under investigation.

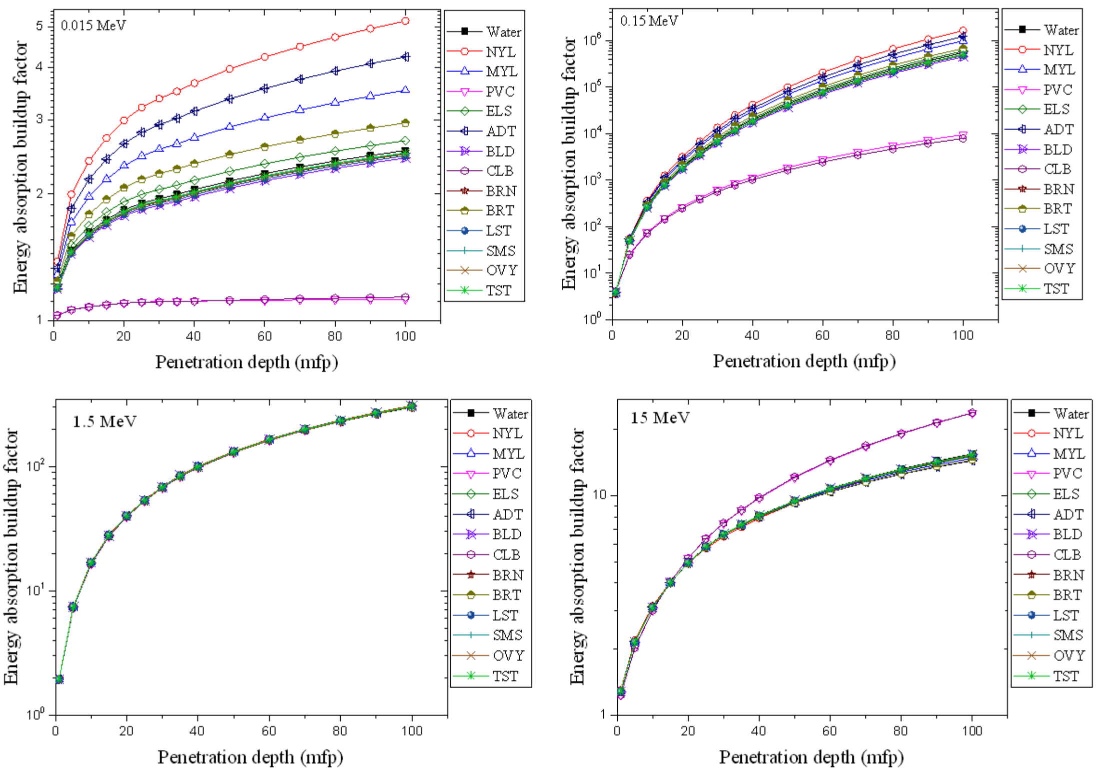

Fig. 16. Variation of energy absorption buildup factor with the penetration depth

Generally, EABF which has similar behaviour with EBF (not shown) are very low at high and low energies with minimal difference as penetration depth increases. Below 40 mfp, the buildup factors grow rapidly as the penetration depth increases. However, the growth slows down as the penetration depth goes beyond this level, up to 100 mfp. As the penetration depth of photons increases, they suffer more collisions (scatterings) leading to loss of energy and some of photons with sufficient energy will interact by photoelectric effect, which makes them to disappear in the material. This ensures that the buildup factors do not rise indefinitely as the penetration depth goes beyond 40 mfp. The values of EABF and EBF at 1 mfp are very small for all materials investigated comparatively with those corresponding to higher penetration depth at the same energy. This is due to the fact that buildup factors at this depth are almost entirely based on unscattered and single gamma rays [24].

Influence of Z_{eq} Buildup factor

The chemical composition of each of the 14 considered materials differs; this also play a crucial role in the magnitude of their buildup factors.

Figures 17-20 show the variation of buildup factors at different energies and selected penetration depths (1, 20, 60, and 100 mfp) for the considered tissues and equivalent materials. The buildup factors magnitude and dependence on Z_{eq} vary depending on the considered energy region.

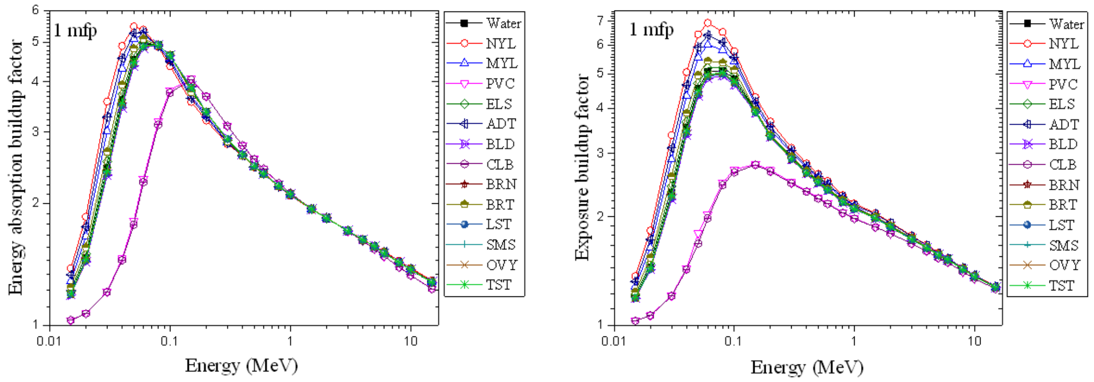

Fig. 17. Comparison of buildup factors for considered tissues and phantom materials at 1 mfp depth

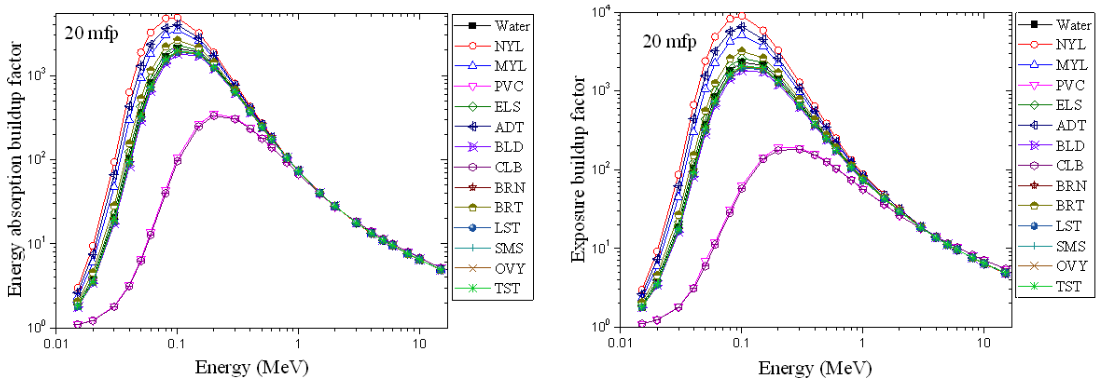

Fig. 18. Comparison of buildup factors for considered tissues and phantom materials at 20 mfp depth

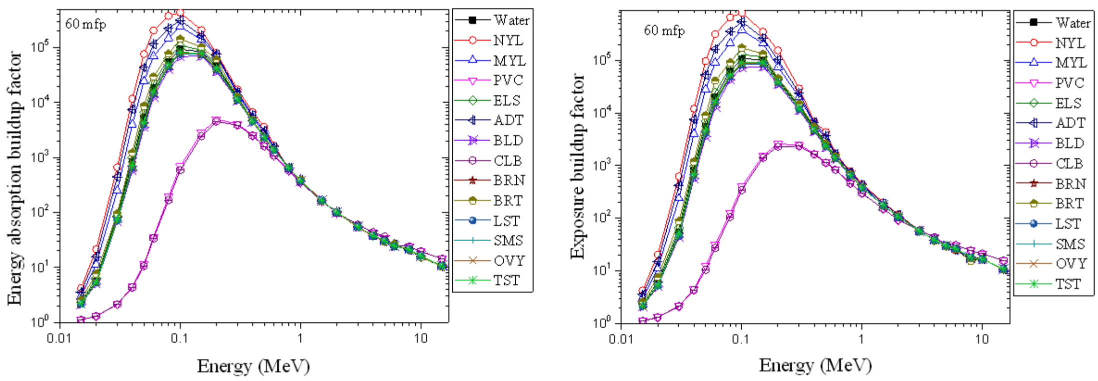

Fig. 19. Comparison of buildup factors for considered tissues and phantom materials at 60 mfp depth

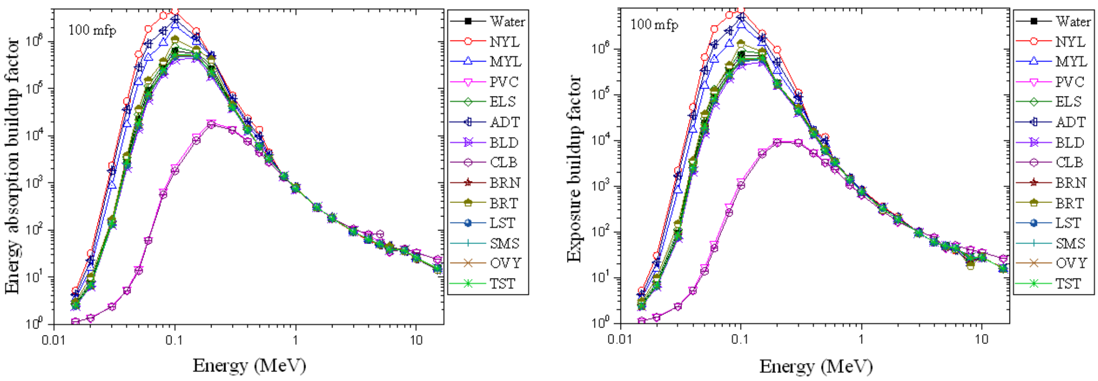

Fig. 20. Comparison of buildup factors for considered tissues and phantom materials at 100 mfp depth

Below 1 MeV, EABF and EBF are inversely proportional to Z_{eq} of the materials. Thus, NYL which has the lowest Z_{eq} is characterized by the highest buildup factors, while CLB with the highest Z_{eq} has the lowest buildup factors. However, at 1 MeV, the buildup factors are almost constant for all considered penetration depths, suggesting that Z_{eq} of the material is independent of its chemical composition for all penetration depths, at this energy.

At 15 MeV and penetration depths beyond 40 mfp, the magnitudes of the buildup factors becomes slightly higher for higher Z_{eq} materials.

Standardisation of Computational Procedure

To verify the accuracy and reliability of the data generated in this research, the evaluated EABF and EBF for water (using interpolated G-P parameters, see Table 2) were compared to the values given in the ANS report [5].

The comparison of exposure buildup factors is shown in Figure 21 at the penetration depths of 10, 20, 30 and 40 mfp. The data obtain in the present procedure agree well with the standard data within 5%. It can thus be confidently said that the present procedure using the G-P fitting method and data generated from it are reliable.

Table 2. Energy absorption and exposure G-P fitting parameters for water in the energy range 0.015 MeV–15 MeV

E (MeV)	*G-P energy absorption buildup coefficients*					*G-P exposure buildup coefficients*				
	b	c	a	X_k	d	b	c	a	X_k	d
0.015	1.199	0.458	0.179	13.938	-0.090	1.198	0.456	0.179	14.368	-0.091
0.020	1.465	0.542	0.148	14.696	-0.075	1.454	0.548	0.145	14.834	-0.072
0.030	2.447	0.751	0.084	13.829	-0.042	2.342	0.781	0.069	16.035	-0.043
0.040	3.604	1.132	-0.020	13.517	0.002	3.543	1.135	-0.021	13.515	0.003
0.050	4.531	1.471	-0.084	13.685	0.034	4.551	1.472	-0.084	13.695	0.034
0.060	4.940	1.747	-0.127	13.720	0.056	5.057	1.748	-0.127	13.715	0.056
0.080	4.928	2.066	-0.168	13.572	0.075	5.102	2.082	-0.170	13.519	0.077
0.100	4.644	2.163	-0.176	14.086	0.077	4.841	2.174	-0.177	14.113	0.077
0.150	3.838	2.205	-0.179	14.405	0.073	3.922	2.254	-0.185	14.301	0.078
0.200	3.365	2.159	-0.176	14.375	0.074	3.356	2.243	-0.188	13.688	0.078
0.300	2.872	2.013	-0.163	14.152	0.064	2.914	2.041	-0.166	14.133	0.067
0.400	2.636	1.871	-0.147	14.147	0.058	2.663	1.898	-0.151	14.123	0.061
0.500	2.471	1.765	-0.135	14.204	0.054	2.505	1.776	-0.137	14.167	0.055
0.600	2.365	1.667	-0.122	14.277	0.049	2.383	1.683	-0.125	14.220	0.050
0.800	2.208	1.531	-0.102	14.295	0.041	2.212	1.555	-0.107	14.140	0.045
1.000	2.106	1.428	-0.086	14.446	0.035	2.110	1.445	-0.090	14.170	0.038
1.500	1.934	1.276	-0.060	14.351	0.026	1.982	1.283	-0.062	14.450	0.027
2.000	1.838	1.173	-0.039	14.160	0.016	1.873	1.182	-0.041	13.965	0.019
3.000	1.711	1.054	-0.012	13.251	0.004	1.731	1.060	-0.014	13.217	0.005
4.000	1.628	0.984	0.005	13.753	-0.005	1.639	0.988	0.004	19.427	-0.006
5.000	1.566	0.937	0.018	14.094	-0.012	1.567	0.940	0.018	13.929	-0.012
6.000	1.504	0.922	0.023	15.311	-0.017	1.520	0.904	0.028	13.185	-0.017
8.000	1.430	0.875	0.037	12.067	-0.021	1.430	0.880	0.035	13.762	-0.023
10.000	1.369	0.866	0.039	14.326	-0.022	1.366	0.866	0.039	13.485	-0.022
15.000	1.276	0.839	0.048	15.358	-0.034	1.273	0.841	0.047	15.130	-0.032

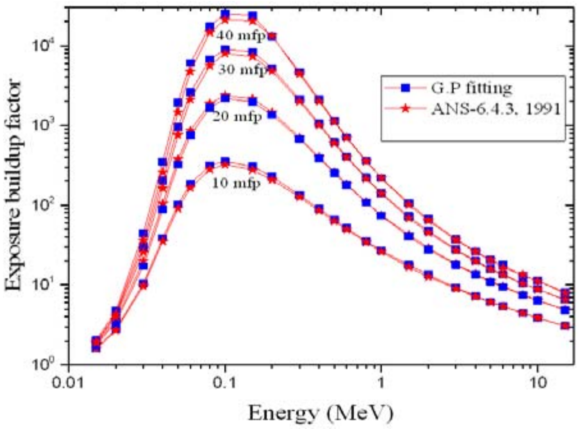

Fig. 21. Comparison of calculated and standard values of EBF of water at 10, 20, 30 and 40 mfp

Conclusions

The accurate evaluation of radiation dose to patients and personnel during medical procedures involving the use of ionising radiation is a vital component of radiation protection. Radiation protection ensures limitation of unnecessary radiation exposure of humans and the environment without compromising the benefits associated with radiation applications. Photon buildup factors are parameters required for accurate dose determination in human tissues and phantom materials.

Ten tissues and four substitute (phantom) materials have been investigated. The equivalent atomic number Z_{eq}, the photon exposure buildup factor (EBF) and the energy absorption buildup factors (EABF) corresponding to the investigated materials were calculated and presented.

Before mentioned parameters have been evaluated in the energy region of 0.015-15 MeV and for penetration depths up to 100 mfp using the well-known G-P fitting method. The buildup parameters were discussed as a function of Z_{eq}, penetration depths and energy.

The evaluated Z_{eq} for all the considered materials showed variations with photon energy and their magnitudes were dictated by their chemical compositions. The values of the equivalent atomic number also suggested that water can be used as a substitute material for soft tissues while Mylar and PVC are good substitute materials for adipose tissues and collar bones, respectively.

The EABF and EBF changes with photon energy in similar pattern for all the materials and having maximum values at energy range of 0.1 – 1 MeV. The changes in both buildup factors depended on chemical composition of the material (Z_{eq}), photon energy and penetration depth. However at 1.5 MeV buildup factors were independent of elemental composition for all penetration depth.

The data presented in this report are useful for accurate dose determination in human tissues and it also suggest good substitute materials for the construction phantoms used in radiation dosimetry and research.

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