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Pocket formula for mass attenuation coefficient, effective atomic number, and electron density of human tissues

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Abstract We have proposed a pocket formula for mass attenuation coefficient (μ/ρ), mass energy absorption coefficient (μ_{en}/ρ), and effective atomic number (Z_{eff}) in different tissues of human organs. We have also assigned a new chemical formula for all studied tissues based on their composition. We have introduced a new parameter called effective composition index (C_{eff}). Based on this, we have introduced a new method to compute the effective atomic number. The evaluated photon interaction parameters are graphically represented. The evaluated average, maximum, minimum, and standard deviations of effective atomic number are tabulated. The proposed formula produces a mass attenuation coefficient, mass energy absorption coefficient, and effective atomic number from their composition

Keywords Effective atomic number · Mass attenuation coefficient · Tissues

1 Introduction

These attenuation coefficients are extensively used in shielding and dosimetric computations which are strongly dependent on the energy of photon and composition of elements of interacting medium. The knowledge of attenuation in tissues is also useful in the mammographic examination which is the most effective method for early diagnosis of breast cancer. The attenuation coefficient and effective atomic number are fundamental parameters in radiology. Literature survey shows that there were several works on theoretical measurements of mass attenuation coefficients of dosimetric interest [1–3].

Hubble and Seltzer [4] gave attenuation coefficients data for the elements and compounds. Berger and Hubbel [2] developed the software called XCOM for calculating mass attenuation coefficients. Gerward et al. [5] developed WinXCom programme to calculate mass attenuation coefficients. Hine [6] introduced the concept of Z_{eff}. This parameter is useful in selecting a tissue substitute. A literature survey shows that some researchers have measured or calculated effective atomic number in biological materials [7–9].

Kurudirek and Onaran [10] studied the Z_{eff} of biomolecules for electron, proton, alpha particle, and photon interactions. Kurudirek [11] also studied Z_{eff} and N_e of human tissues. The same workers [12] also studied Z_{eff} of dosimetric materials for different interactions. Previous workers [13–18] measured the X-ray and gamma interaction parameters in some compounds of dosimetric interest. We also reported theoretical studies on the X-ray and gamma interaction parameters of biological samples [19–26].

Tissue equivalent materials are required for dose distribution studies in the radiotherapy and diagnosis. The photon interaction parameters in the tissues of human organs are important for the preparation of tissue equivalent materials. The tissue equivalent materials and tissues should have a similar behaviour with photons.

In the present work, we have proposed a new semi-empirical formula for photon interaction parameters such as mass attenuation coefficient, mass energy absorption coefficient, and effective atomic number in different tissues of human

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organs [kidney, liver, lung, lymph, muscle, ovary, pancreas, cartilage, red marrow, spongiosa, yellow marrow, skin, spleen, testis, thyroid, skeleton cortical bone, skeleton cranium skeleton femur, skeleton humerus, skeleton mandible, skeleton ribs (second, sixth), skeleton ribs (tenth), skeleton sacrum, skeleton spongiosa, skeleton vertebral column (c4), and skeleton vertebral column (D6, L3)]. In the second section of the paper, we have explained the proposed empirical formula. The third section of the paper describes the comparison of experimental results with the present work.

2 Methodology

2.1 Semi-empirical formula for effective atomic number (Z_{eff}) in terms of composition

To establish the exact relation between effective atomic number and composition, we have introduced a new parameter called effective composition index (C_{eff}). In general, it is the ratio of the sum of the product of composition and atomic weight of elements in large proportion to one plus the sum of the product of composition and atomic weight of remaining elements. The major elements present in the tissues of human organs are H, C, N, and O. Thus, effective composition index (C_{eff}) for tissues of human organ is defined as the ratio between the sum of the product of composition and atomic weight of H, C, N, and O to one plus sum of the product of composition and atomic weight of reaming elements in the tissue.

$$C_{\text{eff}} = \frac{C_{\text{H}}A_{\text{H}} + C_{\text{C}}A_{\text{C}} + C_{\text{N}}A_{\text{N}} + C_{\text{O}}A_{\text{O}}}{1 + C_{\text{Ca}}A_{\text{Ca}} + C_{\text{P}}A_{\text{P}} + C_{\text{Mg}}A_{\text{Mg}} + C_{\text{S}}A_{\text{S}} + C_{\text{Cl}}A_{\text{Cl}} + C_{\text{K}}A_{\text{K}} + C_{\text{Fe}}A_{\text{Fe}} + C_{\text{I}}A_{\text{I}}}. \tag{1}$$

In the above equation, C_{H}, C_{C}, C_{N}, C_{O}, C_{Ca}, C_{P}, C_{Na}, C_{Mg}, C_{S}, C_{Cl}, C_{K}, C_{Fe}, and C_{I} are compositions of the elements indicated in the corresponding subscripts. A_{H}, A_{C}, A_{N}, A_{O}, A_{Ca}, A_{P}, A_{Na}, A_{Mg}, A_{S}, A_{Cl}, A_{K}, A_{Fe}, and A_{I} are atomic weights of the elements indicated in the corresponding subscripts. In the numerator of the above equation, we have considered the composition and atomic weight of H, C, N, and O because these elements are major elemental contents of tissue.

In the denominator, the remaining elemental composition is considered.

The equation of effective composition index (C_{eff}) for a single element is reduced to

$$C_{\text{eff}} = C_i A_i. \tag{2}$$

We have calculated the effective composition index (C_{eff}) for all tissues of human organs. A search was made for their best parametrization with the effective atomic number. Finally, we have established relation between effective atomic number (Z_{eff}) and effective composition index (C_{eff}).

$$Z_{\text{eff}} = \begin{cases} 1\big/(2.04541353 \times 10^{-2}\ln(EC_{\text{eff}}) + 0.2074035539) & \text{for } 1-500\text{ keV} \\ 9.301386273 \times 10^{-6}\,(EC_{\text{eff}}) + 4.245546293 & \text{for } 0.5-20\text{ MeV} \end{cases}. \tag{3}$$

In Eq. (3), E represents photon energy in MeV. Effective atomic number can be calculated with the simple inputs of photon energy (E) and effective composition index (C_{eff}). The effective composition index can be calculated using their composition. Thus, Eq. (3) represents the simple semi-empirical formula which produces the effective atomic number using their composition.

2.2 Semi-empirical formula for mass attenuation and energy absorption coefficients

Most of the tissues of human organs consisting of elements such as H, C, N, O, Ca, P, Na, Mg, S, Cl, K, Fe, and I are in their elemental composition. We have studied the variation of mass attenuation and energy absorption coefficients with atomic number at different energies for the elements which are constituents of tissues of human organs. We have studied the variation of the mass attenuation coefficient (μ/ρ) with energy and atomic number. It is observed from this study that the mass attenuation coefficients (μ/ρ) do not vary linearly with energy and atomic number. To select the best fit for mass attenuation coefficients in the low-energy region (1–100 keV), we have studied suitable functions such as $\alpha_1 E^{\alpha_2} + \alpha_3 E^{\alpha_4}$, $\alpha_1 + \frac{\alpha_2}{E} + \frac{\alpha_3}{E^2} + \frac{\alpha_4}{E^3}$, $\frac{1}{\alpha_1 E^2 + \alpha_2 E + \alpha_3}$, $\frac{\alpha_1 E^{\alpha_2} + \alpha_3}{E^{\alpha_4} + \alpha_5}$, $(\alpha_1 E^{\alpha_2} + \alpha_3)$, $\alpha_1 \exp(\alpha_2 E^{\alpha_3}) + \alpha_4$, $\alpha_1 \exp(\alpha_2 (\ln E + \alpha_3)^2) + \alpha_4$, $\frac{\alpha_1}{((E+\alpha_2)^2+1)^{\alpha_3}} + \alpha_4$, $\alpha_1 \exp(\frac{\alpha_2}{E} + \alpha_3 \ln E)$, $\alpha_1 \exp(\alpha_2 E) + \alpha_3 \exp(\alpha_4 E)$, $\alpha_1 E + \alpha_2 \exp(\alpha_3 E) + \alpha_4$, $\beta_1 E + \beta_2 + \frac{\beta_3}{E} + \beta_4 \ln E$, $\delta_1 E + \delta_2 \exp(\delta_3 E) + \delta_4$, and polynomial function $(\alpha_1 E^4 + \alpha_2 E^3 + \alpha_3 E^2 + \alpha_4 E + \alpha_5)$, where α' s are functions of atomic number [$\alpha = \alpha(Z)$]. Among these functions, the double exponential function such as $\alpha_1 E^{\alpha_2} + \alpha_3$ is the best suitable function. This function is also valid for the low-energy region (1–100 keV) and for elements H, C, N, O, Ca, P, Na, Mg, S, Cl, K, Fe, and I. Hence, we have fit this exponential function such as $\alpha_1 E^{\alpha_2} + \alpha_3$ to the mass attenuation coefficient data for the low-energy region (1–100 keV) for elements H, C, N, O, Ca, P, Na, Mg, S, Cl, K, Fe, and I.

$$\frac{\mu}{\rho} = \sum_{i=0}^{3} \alpha_i Z^i \, E^{\left(\sum_{i=0}^{3} \beta_i Z^i\right)} + \sum_{i=0}^{4} \delta_i Z^i \quad \text{for } 1-100 \text{ keV}, \tag{4}$$

here α_i, β_i, and δ_i are fitting parameters which are given in Table 1.

We have also formulated the equation for the mass attenuation coefficient (μ/ρ) and the product of energy and atomic number in the energy region 100 keV to 20 MeV for elements H, C, N, O, Ca, P, Na, Mg, S, Cl, K, Fe, and I

$$\frac{\mu}{\rho} = 1.591(ZE)^{-0.3865} \quad \text{for } 0.1-20 \text{ MeV}. \tag{5}$$

We have also fit the following nonlinear function to mass attenuation coefficients (μ_{en}/ρ) in the low-energy region (1–100 keV) for elements H, C, N, O, Ca, P, Na, Mg, S, Cl, K, Fe, and I:

$$\frac{\mu_{en}}{\rho} = \sum_{i=0}^{7} \varphi_i Z^i \, E^{\left(\sum_{i=0}^{7} \psi_i Z^i\right)} + \sum_{i=0}^{7} \chi_i Z^i \quad \text{for } 1-100 \text{ keV}. \tag{6}$$

here φ_i, ψ_i, and χ_i are fitting parameters which are given in Table 2.

The proposed formula for the mass energy absorption coefficient (μ_{en}/ρ) and the product of the energy and atomic number in the energy region 100 keV to 20 MeV for elements H, C, N, O, Ca, P, Na, Mg, S, Cl, K, Fe, and I is:

$$\frac{\mu_{en}}{\rho} = -3.1228 \times 10^{-3} \ln(ZE) + 5.0891 \times 10^{-2} \quad \text{for } 0.1-20 \text{ MeV}. \tag{7}$$

The mass attenuation coefficient and mass energy absorption coefficient of tissues of human organs at different energies can be expressed by substituting $Z = Z_{eff}$ in Eqs. (1) and (2):

$$\frac{\mu}{\rho} = \begin{cases} \left(\sum_{i=0}^{3} \alpha_i Z_{eff}^i\right) E^{\left(\sum_{i=0}^{3} \beta_i Z_{eff}^i\right)} + \left(\sum_{i=0}^{4} \delta_i Z_{eff}^i\right) & \text{for } 1-100 \text{ keV} \\ 1.591(Z_{eff}E)^{-0.3865} & \text{for } 0.1-20 \text{ MeV} \end{cases}, \tag{8}$$

and

$$\frac{\mu_{en}}{\rho} = \begin{cases} \left(\sum_{i=0}^{7} \varphi_i Z_{eff}^i\right) E^{\left(\sum_{i=0}^{7} \psi_i Z_{eff}^i\right)} + \left(\sum_{i=0}^{7} \chi_i Z_{eff}^i\right) & \text{for } 1-100 \text{ keV} \\ -3.1228 \times 10^{-3} \ln(ZE) + 5.0891 \times 10^{-2} & \text{for } 0.1-20 \text{ MeV} \end{cases}. \tag{9}$$

Equations (3) and (4) are simple semi-empirical formulae which represent the mass attenuation coefficient (μ/ρ) and mass energy absorption coefficient (μ_{en}/ρ) in terms of the effective atomic number (Z_{eff}) of tissues. In Eqs. (3) and (4), E represents photon energy in keV. Both these coefficients can be calculated with the simple input of effective atomic number (Z_{eff}) at a given energy.

Table 1 Fitting parameters for mass attenuation coefficients (μ/ρ)

	$i = 0$	$i = 1$	$i = 2$	$i = 3$	$i = 4$
α_i	10,757.14872	− 3540.820395	398.4373505	− 4.461736803	0
β_i	− 3.343463789	$6.12684539 \times 10^{-2}$	$-2.825112754 \times 10^{-3}$	$4.967048249 \times 10^{-5}$	0
δ_i	0.4320534583	$-8.406094275 \times 10^{-2}$	8.3504118×10^{-3}	$-3.691850298 \times 10^{-4}$	$5.714514667 \times 10^{-6}$

Table 2 Fitting parameters for mass attenuation coefficients (μ_{en}/ρ)

	Φ_{i}	Ψ_i	X_i
$i = 0$	$-$ 6183.518517	$-$ 3.356499096	$3.445436562 \times 10^{-1}$
$i = 1$	9775.049268	$+ 5.501861004 \times 10^{-2}$	$7.017102505 \times 10^{-2}$
$i = 2$	$-$ 4419.256446	$1.769339873 \times 10^{-2}$	$- 7.455569824 \times 10^{-2}$
$i = 3$	928.8872984	$- 6.915457646 \times 10^{-3}$	$1.881469124 \times 10^{-2}$
$i = 4$	$-$ 99.72245142	$+ 9.55841425 \times 10^{-4}$	$- 2.214979366 \times 10^{-3}$
$i = 5$	+ 5.829884688	$- 6.382510627 \times 10^{-5}$	$1.346734218 \times 10^{-4}$
$i = 6$	$-$ 0.173724236	$2.059213322 \times 10^{-6}$	$- 4.080025291 \times 10^{-6}$
$i = 7$	$2.05344172 \times 10^{-3}$	$-2.563187022 \times 10^{-8}$	$4.856052612 \times 10^{-8}$

Table 3 Equivalent chemical formula for tissues of human organs

Tissue	Chemical formula
Adipose tissue	$H_{4010}C_{1765}N_{18}O_{616}Na_2S_1Cl_1$
Blood	$H_{5652}C_{511}N_{132}O_{2600}P_2Na_2S_3Cl_5K_3Fe_1$
Brain	$H_{1702}C_{194}N_{25}O_{713}P_2Na_2S_3Cl_5K_3$
Breast	$H_{3729}C_{980}N_{76}O_{1168}P_1Na_2Cl_1$
Cell nucleus	$H_{843}C_{60}N_{18}O_{372}P_7S_1$
Eye lens	$H_{3377}C_{576}N_{144}O_{1431}P_1Na_2S_3Cl_1$
GI tract	$H_{4112}C_{374}N_{61}O_{1835}P_1Na_2S_1Cl_2K_1$
Heart	$H_{5707}C_{563}N_{128}O_{2562}P_2Na_2S_3Cl_5K_3Fe_1$
Kidney	$H_{4096}C_{440}N_{86}O_{1814}Ca_1P_3Na_3S_2Cl_2K_2$
Liver	$H_{1764}C_{205}N_{38}O_{793}P_2Na_2S_2Cl_1K_1$
Lung	$H_{1998}C_{171}N_{43}O_{915}P_2Na_2S_2Cl_2K_1$
Lymph	$H_{3436}C_{109}N_{25}O_{1667}Na_4S_1Cl_4$
Muscle	$H_{3588}C_{422}N_{86}O_{1573}P_2Na_2S_3Cl_1K_4$
Ovary	$H_{2037}C_{151}N_{33}O_{938}P_1Na_2S_1Cl_1K_1$
Pancreas	$H_{3372}C_{451}N_{50}O_{1391}P_2Na_3S_1Cl_2K_2$
Cartilage	$H_{1126}C_{97}N_{19}O_{550}P_8Na_3S_3Cl_1$
Red marrow	$H_{5818}C_{1925}N_{136}O_{1532}$
Spongiosa	$H_{4710}C_{1878}N_{112}O_{1281}Ca_{103}P_{61}Na_2Mg_2S_3Cl_3K_1Fe_1$
Yellow marrow	$H_{4045}C_{1901}N_{18}O_{512}Na_2S_1Cl_1$
Skin	$H_{3879}C_{664}N_{117}O_{1576}P_1Na_3S_2Cl_3K_1$
Spleen	$H_{2349}C_{216}N_{53}O_{1065}P_2Na_1Cl_1K_2$
Testis	$H_{3257}C_{255}N_{44}O_{1483}P_1Na_3S_2Cl_2K_2$
Thyroid	$H_{13095}C_{1257}N_{217}O_{5909}P_4Na_{11}S_4Cl_7K_3I_1$
Skeleton cortical bone	$H_{776}C_{297}N_{69}O_{625}Ca_{129}P_{76}Na_1Mg_2S_2$
Skeleton cranium	$H_{1140}C_{406}N_{66}O_{625}Ca_{101}P_{60}Na_1Mg_2$
Skeleton femur	$H_{2462}C_{1018}N_{71}O_{815}Ca_{114}P_{63}Na_2Mg_1S_1Cl_2l_1$
Skeleton humerus	$H_{1447}C_{635}N_{54}O_{561}Ca_{92}P_{55}Na_1Mg_1S_2$
Skeleton mandible	$H_{1049}C_{381}N_{67}O_{625}Ca_{107}P_{64}Na_1Mg_2S_2$
Skeleton ribs (second, sixth)	$H_{2483}C_{856}N_{109}O_{1065}Ca_{128}P_{76}Na_2Mg_2S_4Cl_1l_1$
Skeleton ribs (tenth)	$H_{2172}C_{765}N_{112}O_{1061}Ca_{152}P_{91}Na_2Mg_2S_4Cl_1K_1$
Skeleton sacrum	$H_{4100}C_{1404}N_{148}O_{1529}Ca_{137}P_{81}Mg_2S_3Cl_2K_1Fe_1$
Skeleton spongiosa	$H_{4710}C_{1878}N_{112}O_{1281}Ca_{103}P_{61}Na_2Mg_2S_3Cl_3K_1Fe_1$
Skeleton vertebral column (C4)	$H_{3491}C_{1214}N_{155}O_{1522}Ca_{185}P_{110}Na_2Mg_2S_5Cl_2K_1Fe_1$
Skeleton vertebral column (D6, L3)	$H_{3879}C_{1334}N_{152}O_{1525}Ca_{155}P_{92}Mg_2S_3Cl_2K_1Fe_1$

3 Results and discussions

Based on the composition [32] of elements in the tissues of human organs, we have formulated an equivalent chemical formula. The proposed equivalent chemical formula for tissues of human organs is shown in Table 3. We have calculated mass attenuation coefficients (μ/ρ), mass energy absorption coefficients (μ_{en}/ρ), and effective atomic numbers using the formulae proposed in the present work. The variation of mass energy absorption coefficients (μ_{en}/ρ) with energy for different tissues of human organs for a wide energy range 1 keV–20 MeV is shown in Figs. 1, 2, and 3. A similar variation of mass attenuation coefficients (μ/ρ) with photon energy is also observed. The calculated effective atomic numbers of the tissues of human organs for a wide energy range 1 keV–20 MeV are also shown in Figs. 4, 5, and 6. We have also highlighted the average value, maximum value, minimum value, and standard deviation of the calculated effective atomic number of tissues of human organs for a wide energy range 1 keV–20 MeV. These values are also presented in Table 4.

To verify the validity of the proposed formula, we have compared the values produced by the present work with the

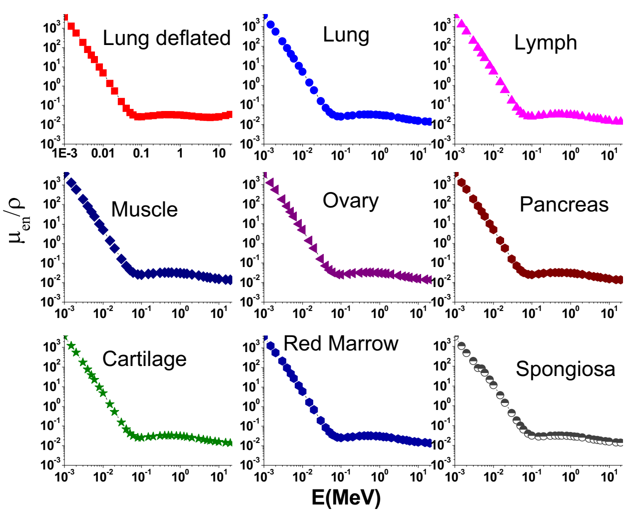

Fig. 1 (Colour online) Variation of mass energy absorption coefficient of some tissues with photon energy (lung, lymph, muscle, ovary, pancreas, cartilage, red marrow, spongiosa)

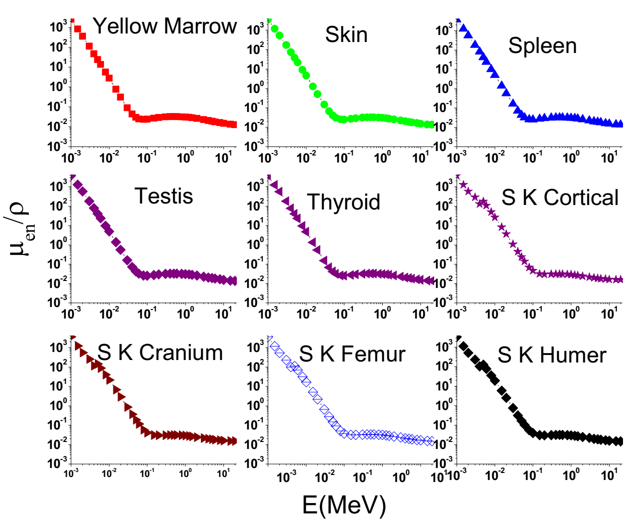

Fig. 2 (Colour online) Variation of mass energy absorption coefficient of some tissues (yellow marrow, skin, spleen, testis, thyroid, skeleton cortical bone, skeleton cranium skeleton femur, skeleton humerus) with photon energy

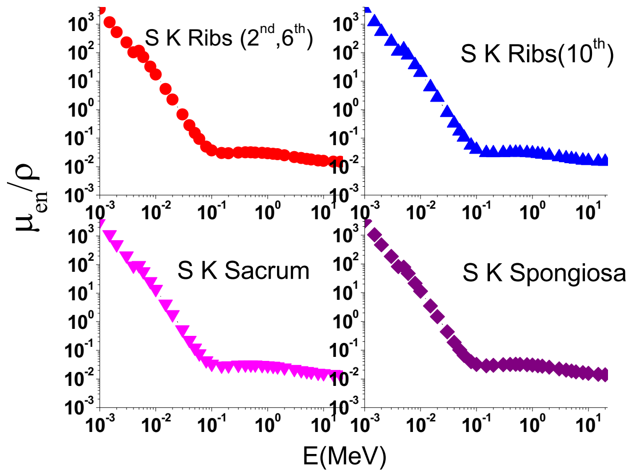

Fig. 3 (Colour online) Variation of mass energy absorption coefficient of some tissues [skeleton ribs (second, sixth), skeleton ribs (tenth), skeleton sacrum, skeleton spongiosa] with photon energy

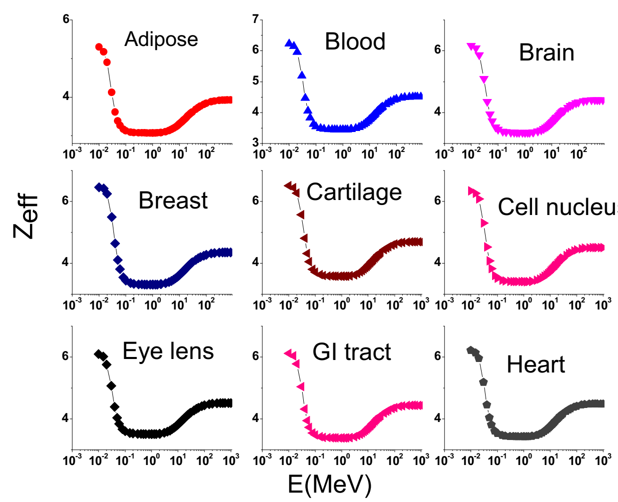

Fig. 4 (Colour online) Variation of effective atomic number of some tissues with photon energy (adipose, blood, brain, breast, cartilage, cell nucleus, eye lens, GI tract, heart)

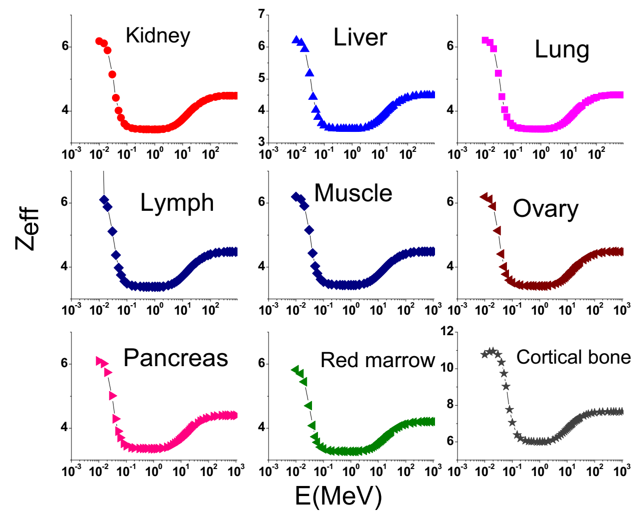

Fig. 5 (Colour online) Variation of effective atomic number of some tissues (kidney, liver, lung, lymph, muscle, ovary, pancreas, red marrow, cortical bone) with photon energy

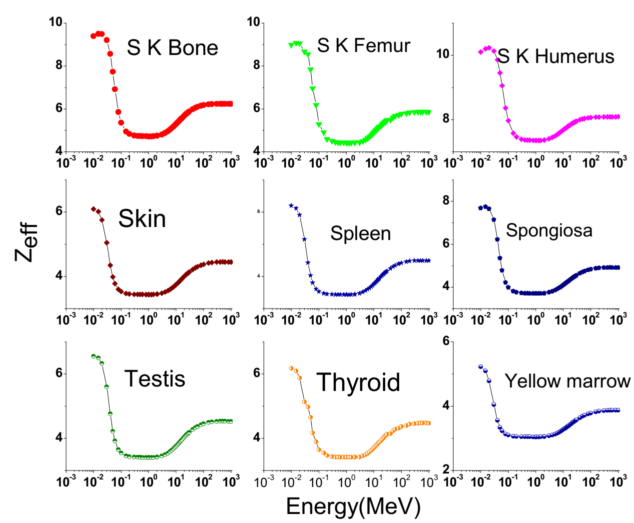

Fig. 6 (Colour online) Variation of effective atomic number of some tissues (SK bone, skeleton femur, skeleton humerus, skin, spleen, spongiosa, testis, thyroid, yellow marrow) with photon energy

Table 4 Statistics of computed effective atomic numbers

Tissue	Z_{eff}			
	Average	Max.	Min.	SD
Adipose	3.520	5.301	3.074	0.497
Blood	4.054	6.224	3.448	0.648
Brain	3.956	6.168	3.354	0.652
Breast	3.946	6.455	3.310	0.736
Cartilage	4.227	6.511	3.578	0.692
Cell nucleus	4.037	6.339	3.401	0.687
Eye lens	4.069	6.094	3.506	0.598
Gi tract	3.972	6.121	3.379	0.635
Heart	4.032	6.217	3.427	0.651
Kidney	4.021	6.185	3.422	0.643
Liver	4.037	6.203	3.437	0.644
Lung deflated	4.041	6.215	3.435	0.649
Lymph	3.996	6.200	3.381	0.617
Muscle	4.031	6.200	3.434	0.642
Ovary	4.012	6.190	3.407	0.648
Pancreas	3.941	6.095	3.357	0.635
Red marrow	3.789	5.819	3.269	0.576
Skeleton cortical bone	7.283	10.949	5.994	1.335
Skeleton cranium	6.196	9.896	5.009	1.289
Skeleton femur	5.182	8.793	4.159	1.181
Skeleton humerus	5.618	9.295	4.512	1.244
Skeleton mandible	6.432	10.132	5.216	1.306
Skeleton ribs(second, sixth)	5.446	9.035	4.391	1.193
Skeleton ribs (tenth)	5.854	9.496	4.721	1.250
Skeleton sacrum	4.979	8.352	4.039	1.088
Skeleton spongiosa	4.540	7.751	3.705	0.995
Skeleton vertebral column	5.468	9.076	4.426	1.165
Skeleton vertebral column	8.009	10.230	7.350	0.771
Skin	4.008	6.095	3.437	0.613
Spleen	4.032	6.194	3.430	0.644
Spongiosa	4.540	7.751	3.705	0.995
Testis	4.076	6.553	3.405	0.742
Thyroid	4.002	6.096	3.411	0.590
Yellow marrow	3.476	5.227	3.045	0.483

experimental values available in the literature. The comparison of mass attenuation coefficients produced by the present formula with that of experimental values is shown in Table 5. From this table, it is clear that the values produced by the present formula agree well with the experiments. In the first stage of the work, we have established the relation between effective atomic number and elemental composition of tissues. The proposed new parameter effective composition index (C_{eff}) helps in achieving an accurate relation between effective atomic number and elemental composition of the tissue at a given energy. In the second stage, we have established the exact relation between effective atomic number, mass attenuation coefficients (μ/ρ), and mass energy absorption coefficients (μ_{en}/ρ). Hence, this set of simple formulae produces mass attenuation coefficients (μ/ρ) and mass energy absorption coefficients (μ_{en}/ρ) from the elemental composition at a given energy.

Table 5 Comparison of the present work with experiments

Tissue	Energy (keV)	Mass attenuation coefficient (cm^2/g) Experimental values [10]	Present work	WinXCom [5]	Tissue	Energy (keV)	Mass attenuation coefficient (cm^2/g) Experimental values [10]	Present work	WinXCom [5]
Adipose	8	6.0000 [27]	5.560	5.501	Pancreas	27	0.4192 [29]	0.4156	0.410
	11	2.4000 [27]	2.596	4.90		60	0.20673 [29]	0.2027	0.203
	15	1.0295 [27]	1.118	1.10		122	0.1586 [29]	0.1601	0.162
	20	0.5200 [27]	0.569	0.510		279	0.1211 [29]	0.1175	0.110
	30	0.2947 [27]	0.387	0.318		662	0.08615 [29]	0.0749	0.079
Liver	30	0.3868 [28]	0.429	0.410	Lung	27	0.32285 [29]	0.3347	0.330
	40	0.2821 [28]	0.218	0.250		60	0.15904 [29]	0.1548	0.150
	50	0.2415 [28]	0.203	0.250		122	0.11714 [29]	0.1352	0.131
	60	0.2198 [28]	0.199	0.210		279	0.08667 [29]	0.089	0.080
	70	0.2145 [28]	0.181	0.190		662	0.06267 [29]	0.066	0.065
	80	0.1962 [28]	0.171	0.180	Kidney	27	0.4323 [29]	0.4369	0.421
	90	0.19056 [28]	0.166	0.170		60	0.208 [29]	0.2062	0.210
	100	0.1887 [28]	0.161	0.160		122	0.157 [29]	0.1601	0.159
	110	0.1557 [28]	0.159	0.151		279	0.121 [29]	0.1370	0.135
						662	0.085 [29]	0.0909	0.089
Kidney	30	0.3705 [28]	0.388	0.380	Breast	8	9.157 [30]	8.708	8.501
	40	0.2657 [28]	0.245	0.250		10	5.392 [30]	4.454	4.100
	50	0.2343 [28]	0.221	0.231		12	3.382 [30]	2.91	3.103
	60	0.2076 [28]	0.197	0.205		14	2.098 [30]	1.811	2.103
	70	0.1895 [28]	0.196	0.191	Bone	140	0.1255 [31]	0.130	0.129
	80	0.19142 [28]	0.190	0.190		364	0.10104 [31]	0.118	0.101
	90	0.1838 [28]	0.171	0.170		662	0.0667 [31]	0.083	0.070
	100	0.1667 [28]	0.177	0.175	Muscle	140	0.1495 [31]	0.142	0.141
	110	0.1876 [28]	0.173	0.172		364	0.09143 [31]	0.102	0.090
						662	0.0771 [31]	0.091	0.082
Brain	27	0.43365 [28]	0.421	0.410	Liver	27	0.416 [29]	0.410	0.410
	60	0.2096 [28]	0.224	0.210		60	0.2085 [29]	0.209	0.210
	122	0.1644 [28]	0.154	0.145		122	0.1557 [29]	0.1607	0.154
	279	0.1231 [28]	0.122	0.132		279	0.1188 [29]	0.1276	0.112
	662	0.0872 [28]	0.103	0.080		662	0.0849 [29]	0.0782	0.078

4 Conclusion

The proposed semi-empirical formula of mass attenuation coefficients (μ/ρ), mass energy absorption coefficients (μ_{en}/ρ), and effective atomic number for tissues of human organs in the energy range 1 keV–20 MeV produces values which agree well with experiments. This formula is the first of its kind, and it is useful in radiotherapy and medical physics.

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