ENERGY ABSORPTION BUILD-UP FACTORS OF VITAL HUMAN ORGANS

NIL KUCUK [1], VISHWANATH PRATAP SINGH [2], GUNJAN GANGWAR [3], NAGAPPA MALLIKARJUN BADIGER [2]

[1] Department of Physics, Uludag University, Gorukle Campus, Bursa, Turkey
[2] Department of Physics, Karnatak University, Dharwad, India
[3] Central Inland Fisheries Research Institutes, Allahabad, India
e-mail: kudphyvps@rediffmail.com

Abstract

Energy absorption build-up factor (EABF) values have been calculated for vital human organs such as brain, heart, kidney, liver, lung, ovary, pancreas, spleen, and tongue, for the photon energy range 0.015–15 MeV and for penetration depths up to 40 mean free paths (mfp). The five-parameter geometric progression (G-P) fitting approximation and ANSI/ANS-6.4.3-1991 (American National Standard) library have been used to calculate EABF. The EABF has been studied as functions of incident photon energy and penetration depth. It is also found that the EABF of human organs significantly change by varying the incident photon energy and the penetration depth. These changes are due to the dominance of different photon interaction processes in different energy regions.

Keywords: *Build-up factor; Gamma-ray; G-P fitting approximation; Human organs*

Introduction

Radiation is widely used in radiation dosimetry and brachytherapy. Some aggressive cancers such as liver, lung, pancreas and ovary cancers are being treated with radiation therapy. Radiation is effective as a cancer treatment because it can kill the cancer cells, however it can also kill or damage nearby cells. In brachytherapy, radioactive seeds are planted in patient's body to destroy cancer tumour while avoiding the surrounding healthy cells [1]. When radiation is used to treat cancer it must be pinpointed very carefully. The user of radioisotopes must be aware how radiation interacts with the human body.

When photons enter the body, they degrade their energy and build-up in the medium, giving rise to secondary radiation which can be estimated by a multiplicative factor, which is called the build-up factor. Thus it is important to consider the photon build-up factor in calculation of radiation dose received by the cancer cells. The biological effect of ionizing radiation on human beings depends on type of radiation, energy, absorbed dose, and organs irradiated. Energy absorption build-up factor (EABF) is defined as the photon build-up factor in which the quantity of interest is the absorbed or deposited energy in the considered medium [2].

When human organs are exposed to X-rays and gamma-rays, the maximum radiation dose to the organ may not be at its surface but somewhere inside, due to the build-up of degraded photons by multiple scattering within the organ.

Recognizing the importance of build-up of such scattered photons, some attempts have been made to compute the EABF values for some human organs. In 2011, Manohara et al. [3] have reported the energy absorption build-up factors of some human organs and tissues. However, only a limited amount of work has been reported in the literature on EABF of the vital human organs. Hence, there is a need for gamma-ray build-up factors of crucial human organs in diagnostics, dosimetry, and radiation therapy for absorbed dose estimations.

It is necessary to study on the build-up of photons in some human organs, for which the build-up factor data cannot be found in any standard database. Only with a correct knowledge of the build-up factors of human organs, energy absorption in the human body can be carefully controlled. These studies will help in estimating safe dose levels for radiotherapy patients and also will be useful in dosimetry and brachytherapy.

In present work, the EABF values for some vital human organs, such as brain, heart, kidney, liver, lung, ovary, pancreas, spleen, and tongue have been calculated, by using the five-parameter geometric progression (G-P) fitting approximation and the ANSI/ANS-6.4.3-1991 standard data [2].

The calculations have been performed for the photon energy range 0.015–15 MeV and for penetration depths up to 40 mean free paths (mfp). The generated build-up factor data have been studied as a function of the incident photon energy, and the penetration depth.

Materials and methods

The chemical compositions of the nine vital human organs considered in the present study are given in Table 1. These data have been taken from the literature [4, 5]. The computations have been carried out in three steps, presented in the following.

Table 1. Chemical composition of vital human organs (fraction by weight)

Nr. crt.	Human Organ	Chemical composition (element: fraction by weight)
1.	Brain	*H*:0.104, *C*:0.161, *N*:0.039, *O*:0.684, *Na*:0.002, *P*:0.003, *S*:0.002, *K*:0.003
2.	Heart	*H*: 0.106, *C*:0.124, *N*:0.025, *O*:0.744, *S*:0.002
3.	Kidney	*H*:0.096, *C*:0.030, *N*:0.122, *O*:0.729, *Na*:0.002, *P*:0.002, *Cl*:0.002, *K*:0.002
4.	Liver	*H*:0.110, *C*:0.041, *N*:0.012, *O*:0.825, *Cl*:0.012
5.	Lung	*H*:0.105, *C*:0.095, *N*:0.025, *O*:0.766, *P*:0.007, *S*:0.002
6.	Ovary	*H*:0.109, *C*:0.046, *N*:0.011, *O*:0.834
7.	Pancreas	*H*:0.107, *C*:0.072, *N*:0.023, *O*:0.800, *S*:0.002
8.	Spleen	*H*:0.105, *C*:0.101, *N*:0.027, *O*:0.765, *S*:0.002
9.	Tongue	*H*:0.107, *C*:0.173, *N*:0.031, *O*:0.683, *P*:0.002, *S*:0.003

Calculation of the equivalent atomic number, Z_{eq}

The equivalent atomic number (Z_{eq}) represents radiation interaction with matter and is a useful parameter to consider in computing absorbed dose, build-up factor and energy absorption, and designing radiation shields. However, the build-up of photons in the medium is mainly due to multiple scattering events by Compton scattering, so that Z_{eq} is derived from the Compton scattering interaction process. The value of Z_{eq} for a given material is energy dependent.

Firstly, the values of the Compton partial attenuation coefficient $(\mu/\rho)_{Compton}$ and the total attenuation coefficients $(\mu/\rho)_{Total}$ were obtained for the elements with Z = 4 to Z = 40 and for the human organs in the energy region 0.015 - 15 MeV, using WinXcom program [6, 7]. Further, the ratio $(\mu/\rho)_{Compton}/(\mu/\rho)_{Total}$ was determined for all the elements and the nine human organs. The values of for the human organs were calculated by matching the ratio $(\mu/\rho)_{Compton}/(\mu/\rho)_{Total}$ of a particular human organ at a selected energy with the corresponding ratio of an element at the same energy. For those cases where the ratio value lies between two ratios for known elements, the value of was interpolated using the following formula:

$$Z_{eq} = \frac{Z_1\left(\log R_2 - \log R\right) + Z_2\left(\log R - \log R_1\right)}{\log R_2 - \log R_1} \qquad (1)$$

where Z_1 and Z_2 are the atomic numbers of the elements corresponding to the ratios R_1 and R_2, respectively, R being the ratio for the biological sample at a specific energy.

Example: Let us consider pancreas and incident photon energy 2 MeV. The ratio $(\mu/\rho)_{Compton}/(\mu/\rho)_{Total}$ for pancreas is 0.992, which lies between the ratios 0.993 and 0.991 corresponding to the elements with $Z_1 = 6$ and $Z_2 = 7$, respectively. Now using these values in Eq.(1) $Z_{eq} = 6.377$ is found. With this method, the values of Z_{eq} for the other human organs at particular energies were computed. The values of Z_{eq} obtained in this way for vital human organs are given in Table 2.

Table 2. Equivalent atomic numbers of vital human organs in the energy range 0.015–15 MeV

E(MeV)	Brain	Heart	Kidney	Liver	Lung	Ovary	Pancreas	Spleen	Tongue
0.015	7.350	7.251	7.550	7.570	7.414	7.333	7.334	7.292	7.211
0.02	7.369	7.266	7.490	7.633	7.431	7.347	7.348	7.306	7.227
0.03	7.368	7.259	7.488	7.635	7.428	7.339	7.341	7.300	7.223
0.04	7.348	7.240	7.464	7.618	7.402	7.316	7.318	7.277	7.204
0.05	7.321	7.211	7.439	7.588	7.376	7.289	7.288	7.253	7.174
0.06	7.301	7.203	7.421	7.575	7.366	7.281	7.287	7.244	7.153
0.08	7.248	7.143	7.367	7.515	7.306	7.237	7.222	7.206	7.120
0.10	7.222	7.145	7.349	7.497	7.293	7.210	7.215	7.184	7.069
0.15	7.122	7.015	7.242	7.407	7.220	7.107	7.013	7.017	7.013
0.2	6.900	6.896	6.918	7.310	6.898	6.887	6.894	6.898	6.712
0.3	7.174	7.169	7.193	7.158	7.172	7.161	7.166	7.172	7.166
0.4	7.253	7.246	7.276	7.234	7.249	7.234	7.246	7.249	7.242
0.5	7.109	6.963	7.258	7.222	7.106	6.951	6.960	6.967	6.959
0.6	7.102	7.097	7.302	7.268	7.281	7.270	7.095	7.099	7.094
0.8	7.054	7.049	7.070	7.342	7.052	7.041	7.047	7.051	7.046
1	6.532	7.216	7.237	7.206	7.218	7.208	7.214	7.217	7.213
1.5	6.893	6.430	6.473	6.724	6.436	6.415	6.427	6.435	6.425
2	6.392	6.533	6.579	6.661	6.538	6.516	6.377	6.386	6.376
3	6.451	6.439	6.674	6.657	6.567	6.540	6.556	6.504	6.371
4	6.427	6.452	6.643	6.604	6.528	6.539	6.518	6.491	6.376
5	6.426	6.442	6.632	6.639	6.559	6.532	6.519	6.474	6.352
6	6.405	6.438	6.648	6.637	6.532	6.529	6.521	6.488	6.319
8	6.429	6.432	6.657	6.630	6.540	6.599	6.530	6.490	6.341
10	6.425	6.441	6.653	6.629	6.549	6.534	6.522	6.474	6.348
15	6.406	6.427	6.635	6.619	6.519	6.539	6.508	6.476	6.335

Calculation of Geometric Progression (G-P) fitting parameters

The Z_{eq} values previously obtained were used to calculate G-P fitting parameters (a, b, c, d, and X_k) for EABF values using the following interpolation formula:

$$P = \frac{P_1\left(\log Z_2 - \log Z_{eq}\right) + P_2\left(\log Z_{eq} - \log Z_1\right)}{\log Z_2 - \log Z_1} \qquad (2)$$

where Z_1 and Z_2 are the atomic numbers of elements between which the Z_{eq} of a given human organ lies, and P_1 and P_2 are the G-P fitting parameters corresponding to the atomic numbers of Z_1 and Z_2, respectively, at a given energy.

G-P fitting parameters of *EABF* for the 23 elements (i.e. Be, B, C, N, O, Na, Mg, Al, Si, P, S, Ar, K, Ca, Fe, Cu, Mo, Sn, La, Gd, W, Pb and U) in the energy region 0.015–15 MeV were taken from the ANSI/ANS-6.4.3 standard reference database [2]. The resulting G-P energy absorption build-up factor coefficients for human organs are given in Tables 3–5.

Table 3. G-P energy absorption build-up factor coefficients of the brain, heart and kidney

E	**Brain**					**Heart**					**Kidney**				
(MeV)	***b***	***c***	***a***	***X_k***	***d***	***b***	***c***	***a***	***X_k***	***d***	***b***	***c***	***a***	***X_k***	***d***
0.015	1.206	0.463	0.176	14.05	-0.088	1.214	0.469	0.172	14.20	-0.085	1.190	0.451	0.183	13.76	-0.093
0.02	1.483	0.549	0.146	14.73	-0.073	1.504	0.557	0.142	14.78	-0.071	1.459	0.539	0.149	14.68	-0.075
0.03	2.505	0.772	0.077	14.32	-0.041	2.565	0.792	0.069	14.82	-0.040	2.440	0.749	0.084	13.78	-0.042
0.04	3.706	1.170	-0.028	13.59	0.006	3.791	1.201	-0.035	13.66	0.009	3.616	1.136	-0.021	13.53	0.002
0.05	4.650	1.524	-0.093	13.78	0.038	4.732	1.559	-0.099	13.84	0.041	4.564	1.486	-0.087	13.71	0.035
0.06	5.016	1.811	-0.136	13.74	0.061	5.057	1.846	-0.141	13.75	0.063	4.967	1.769	-0.130	13.73	0.058
0.08	4.921	2.143	-0.177	13.50	0.078	4.918	2.178	-0.181	13.47	0.080	4.924	2.105	-0.172	13.54	0.077
0.10	4.653	2.209	-0.180	14.30	0.077	4.656	2.223	-0.181	14.36	0.077	4.649	2.188	-0.178	14.20	0.077
0.15	3.771	2.276	-0.187	14.41	0.075	3.752	2.296	-0.189	14.41	0.076	3.793	2.253	-0.184	14.41	0.074
0.2	3.347	2.211	-0.181	14.80	0.076	3.346	2.211	-0.181	14.80	0.076	3.350	2.208	-0.180	14.80	0.076
0.3	2.852	2.041	-0.166	14.19	0.066	2.852	2.041	-0.166	14.19	0.066	2.853	2.039	-0.166	14.19	0.066
0.4	2.628	1.884	-0.149	14.18	0.059	2.628	1.885	-0.149	14.18	0.059	2.629	1.883	-0.149	14.18	0.059
0.5	2.464	1.780	-0.137	14.14	0.055	2.462	1.786	-0.138	14.19	0.056	2.467	1.774	-0.136	14.16	0.055
0.6	2.363	1.677	-0.124	14.25	0.050	2.363	1.678	-0.124	14.25	0.050	2.364	1.672	-0.123	14.26	0.049
0.8	2.203	1.543	-0.105	14.21	0.043	2.203	1.543	-0.105	14.21	0.043	2.203	1.542	-0.105	14.21	0.043
1	2.099	1.443	-0.089	14.49	0.038	2.107	1.429	-0.086	14.60	0.035	2.107	1.429	-0.086	14.59	0.035
1.5	1.932	1.277	-0.060	14.37	0.026	1.937	1.276	-0.060	14.33	0.026	1.936	1.276	-0.060	14.33	0.026
2	1.840	1.171	-0.038	14.29	0.015	1.839	1.172	-0.039	14.21	0.016	1.838	1.172	-0.039	14.18	0.016
3	1.712	1.053	-0.012	13.57	0.003	1.712	1.053	-0.012	13.60	0.003	1.710	1.055	-0.012	13.13	0.004
4	1.627	0.986	0.005	13.49	-0.004	1.627	0.985	0.005	13.53	-0.004	1.628	0.983	0.006	13.81	-0.005
5	1.565	0.940	0.017	14.36	-0.010	1.565	0.940	0.017	14.34	-0.010	1.566	0.937	0.019	14.05	-0.012
6	1.509	0.915	0.025	14.38	-0.017	1.508	0.916	0.025	14.54	-0.017	1.503	0.923	0.022	15.53	-0.017
8	1.430	0.877	0.036	12.08	-0.019	1.430	0.877	0.036	12.08	-0.019	1.430	0.874	0.038	12.06	-0.021
10	1.372	0.864	0.039	14.32	-0.022	1.372	0.864	0.039	14.32	-0.022	1.369	0.866	0.039	14.33	-0.022
15	1.278	0.838	0.048	15.52	-0.034	1.278	0.838	0.048	15.50	-0.034	1.276	0.839	0.048	15.32	-0.034

Table 4. G-P energy absorption build-up factor coefficients of the liver, lung and ovary

E	**Liver**					**Lung**					**Ovary**				
(MeV)	***b***	***c***	***a***	X_k	***d***	***b***	***c***	***a***	X_k	***d***	***b***	***c***	***a***	X_k	***d***
0.015	1.188	0.450	0.184	13.74	-0.093	1.201	0.459	0.178	13.96	-0.089	1.207	0.464	0.175	14.08	-0.087
0.02	1.431	0.529	0.153	14.62	-0.078	1.470	0.544	0.147	14.71	-0.074	1.487	0.550	0.145	14.74	-0.073
0.03	2.361	0.722	0.094	13.12	-0.043	2.473	0.760	0.080	14.05	-0.041	2.521	0.777	0.075	14.45	-0.041
0.04	3.499	1.093	-0.011	13.44	-0.002	3.664	1.154	-0.025	13.56	0.004	3.731	1.179	-0.030	13.61	0.007
0.05	4.455	1.438	-0.079	13.63	0.031	4.610	1.506	-0.090	13.74	0.037	4.674	1.534	-0.095	13.79	0.039
0.06	4.904	1.717	-0.123	13.71	0.054	4.990	1.789	-0.133	13.73	0.059	5.025	1.818	-0.137	13.74	0.061
0.08	4.929	2.059	-0.167	13.58	0.074	4.923	2.125	-0.174	13.52	0.078	4.920	2.147	-0.177	13.50	0.079
0.10	4.644	2.163	-0.176	14.08	0.077	4.651	2.197	-0.179	14.24	0.077	4.654	2.211	-0.180	14.31	0.077
0.15	3.822	2.222	-0.181	14.41	0.073	3.789	2.257	-0.185	14.41	0.075	3.769	2.278	-0.187	14.41	0.076
0.2	3.365	2.173	-0.177	14.53	0.075	3.347	2.211	-0.181	14.80	0.076	3.345	2.213	-0.181	14.80	0.076
0.3	2.851	2.042	-0.166	14.19	0.066	2.852	2.041	-0.166	14.19	0.066	2.851	2.042	-0.166	14.19	0.066
0.4	2.627	1.885	-0.149	14.18	0.059	2.628	1.884	-0.149	14.18	0.059	2.627	1.885	-0.149	14.18	0.059
0.5	2.466	1.776	-0.137	14.16	0.055	2.464	1.781	-0.137	14.14	0.055	2.462	1.786	-0.138	14.21	0.056
0.6	2.364	1.673	-0.123	14.26	0.049	2.364	1.673	-0.123	14.26	0.049	2.364	1.673	-0.123	14.26	0.049
0.8	2.206	1.535	-0.103	14.26	0.042	2.203	1.543	-0.105	14.21	0.043	2.203	1.543	-0.105	14.21	0.043
1	2.107	1.429	-0.086	14.61	0.035	2.107	1.429	-0.086	14.60	0.035	2.107	1.429	-0.086	14.61	0.035
1.5	1.934	1.276	-0.060	14.36	0.026	1.936	1.276	-0.060	14.33	0.026	1.937	1.276	-0.060	14.33	0.026
2	1.838	1.173	-0.039	14.14	0.016	1.839	1.172	-0.039	14.21	0.016	1.839	1.172	-0.039	14.22	0.016
3	1.710	1.055	-0.012	13.16	0.004	1.711	1.054	-0.012	13.34	0.004	1.711	1.054	-0.012	13.39	0.003
4	1.628	0.984	0.005	13.75	-0.005	1.628	0.985	0.005	13.64	-0.005	1.628	0.984	0.005	13.66	-0.005
5	1.566	0.937	0.019	14.04	-0.012	1.566	0.938	0.018	14.16	-0.011	1.566	0.938	0.018	14.20	-0.011
6	1.503	0.923	0.022	15.48	-0.017	1.506	0.919	0.023	14.99	-0.017	1.506	0.919	0.023	14.98	-0.017
8	1.430	0.874	0.038	12.06	-0.021	1.430	0.876	0.037	12.07	-0.020	1.430	0.876	0.037	12.07	-0.020
10	1.369	0.866	0.039	14.33	-0.022	1.370	0.865	0.039	14.33	-0.022	1.370	0.865	0.039	14.33	-0.022
15	1.276	0.839	0.048	15.33	-0.034	1.277	0.839	0.048	15.42	-0.034	1.277	0.839	0.048	15.40	-0.034

Table 5. G-P energy absorption build-up factor coefficients of the pancreas, spleen and tongue

E (MeV)	Pancreas					Spleen					Tongue				
	b	***c***	***a***	X_k	***d***	***b***	***c***	***a***	X_k	***d***	***b***	***c***	***a***	X_k	***d***
0.015	1.207	0.464	0.175	14.07	-0.087	1.211	0.467	0.174	14.14	-0.086	1.218	0.472	0.171	14.25	-0.084
0.02	1.487	0.550	0.145	14.74	-0.073	1.496	0.554	0.144	14.76	-0.072	1.512	0.560	0.141	14.80	-0.070
0.03	2.520	0.777	0.075	14.44	-0.041	2.543	0.785	0.072	14.63	-0.040	2.586	0.799	0.067	14.99	-0.039
0.04	3.729	1.178	-0.030	13.61	0.007	3.761	1.190	-0.033	13.63	0.008	3.819	1.211	-0.037	13.68	0.010
0.05	4.675	1.534	-0.095	13.79	0.039	4.701	1.546	-0.097	13.81	0.040	4.760	1.572	-0.101	13.86	0.042
0.06	5.022	1.816	-0.137	13.74	0.061	5.040	1.831	-0.139	13.74	0.062	5.079	1.864	-0.143	13.75	0.065
0.08	4.920	2.152	-0.178	13.50	0.079	4.920	2.157	-0.178	13.49	0.079	4.917	2.185	-0.181	13.47	0.080
0.10	4.654	2.210	-0.180	14.31	0.077	4.655	2.216	-0.180	14.33	0.077	4.659	2.236	-0.182	14.42	0.077
0.15	3.751	2.296	-0.189	14.41	0.076	3.752	2.296	-0.189	14.41	0.076	3.751	2.296	-0.189	14.41	0.076
0.2	3.346	2.212	-0.181	14.80	0.076	3.347	2.211	-0.181	14.80	0.076	3.313	2.241	-0.184	14.79	0.076
0.3	2.852	2.042	-0.166	14.19	0.066	2.852	2.041	-0.166	14.19	0.066	2.852	2.042	-0.166	14.19	0.066
0.4	2.628	1.885	-0.149	14.18	0.059	2.628	1.884	-0.149	14.18	0.059	2.628	1.885	-0.149	14.18	0.059
0.5	2.462	1.786	-0.138	14.19	0.056	2.462	1.785	-0.138	14.18	0.056	2.462	1.786	-0.138	14.19	0.056
0.6	2.363	1.678	-0.124	14.25	0.050	2.363	1.677	-0.124	14.25	0.050	2.363	1.678	-0.124	14.25	0.050
0.8	2.203	1.543	-0.105	14.21	0.043	2.203	1.543	-0.105	14.21	0.043	2.203	1.543	-0.105	14.21	0.043
1	2.107	1.429	-0.086	14.60	0.035	2.107	1.429	-0.086	14.60	0.035	2.107	1.429	-0.086	14.60	0.035
1.5	1.937	1.276	-0.060	14.33	0.026	1.936	1.276	-0.060	14.33	0.026	1.937	1.276	-0.060	14.33	0.026
2	1.840	1.171	-0.038	14.30	0.015	1.840	1.171	-0.038	14.30	0.015	1.840	1.171	-0.038	14.30	0.015
3	1.711	1.054	-0.012	13.36	0.004	1.711	1.054	-0.012	13.46	0.003	1.712	1.053	-0.012	13.73	0.003
4	1.628	0.985	0.005	13.63	-0.005	1.628	0.985	0.005	13.59	-0.005	1.627	0.986	0.005	13.41	-0.004
5	1.566	0.938	0.018	14.22	-0.011	1.565	0.939	0.017	14.29	-0.011	1.565	0.941	0.017	14.48	-0.010
6	1.506	0.919	0.024	14.94	-0.017	1.507	0.918	0.024	14.78	-0.017	1.511	0.912	0.026	13.96	-0.018
8	1.430	0.876	0.037	12.07	-0.020	1.430	0.876	0.037	12.07	-0.020	1.430	0.879	0.036	12.08	-0.019
10	1.370	0.865	0.039	14.33	-0.022	1.371	0.864	0.039	14.32	-0.022	1.373	0.863	0.039	14.32	-0.022
15	1.277	0.839	0.048	15.43	-0.034	1.278	0.838	0.048	15.46	-0.034	1.279	0.838	0.048	15.59	-0.033

Calculation of energy absorption buildup factors (EABF)
Finally, the *EABF* were computed by using G-P fitting parameters (b, c, a, X_k and d) in the photon energy region 0.015–15 MeV, up to penetration depths of 40 *mfp* with the equations [8, 9] given below:

$$\mathrm{B(E,x)} = 1 + \frac{(b-1)(K^x - 1)}{(K-1)} \quad for \quad \mathrm{K} \neq 1$$
$$\mathrm{B(E,x)} = 1 + (b-1)\,\mathrm{x} \quad for \quad \mathrm{K} = 1 \qquad (3)$$

with

$$\mathrm{K(E,x)} = \mathrm{cx}^{\mathrm{a}} + \mathrm{d}\frac{\left[\tanh\left(\frac{\mathrm{x}}{\mathrm{X_k}} - 2\right) - \tanh(-2)\right]}{\left[1 - \tanh(-2)\right]} \qquad (4)$$
$$for \ \mathrm{x} \leq 40\,\mathrm{mfp}$$

where x is the distance from the source in mean-free-paths and b is the value of the energy absorption build-up factor at 1 *mfp*. The variation of parameter *K(E,x)* represents the photon dose multiplication and the change in the spectrum shape from that at 1 *mfp*, which determined the value of b.

Eq. (4) represents the dependence of K on x; a, c, d, and X_k are the fitting parameters which depend on the attenuating medium and source energy, E (according to [2]).

Results and discussions
The computed G-P energy absorption build-up factor coefficients (presented in Tables 3–5) were used to generate EABF values. In the following paragraphs, we discuss how the build-up factors vary with incident photon energy, and penetration depth, respectively.

Figures 1(a)–1(f) show comparatively the EABF of the nine considered vital human organs for some selected penetration depths of 0.5, 1, 5, 10, 20 and 40 mfp, respectively.

It can be observed that the human organs show similar variations in the continuous energy region based on domination of different photon interaction processes in different energy regions. This is because each of these human organs consists of materials having similar chemical composition (as can be seen in Table 1).

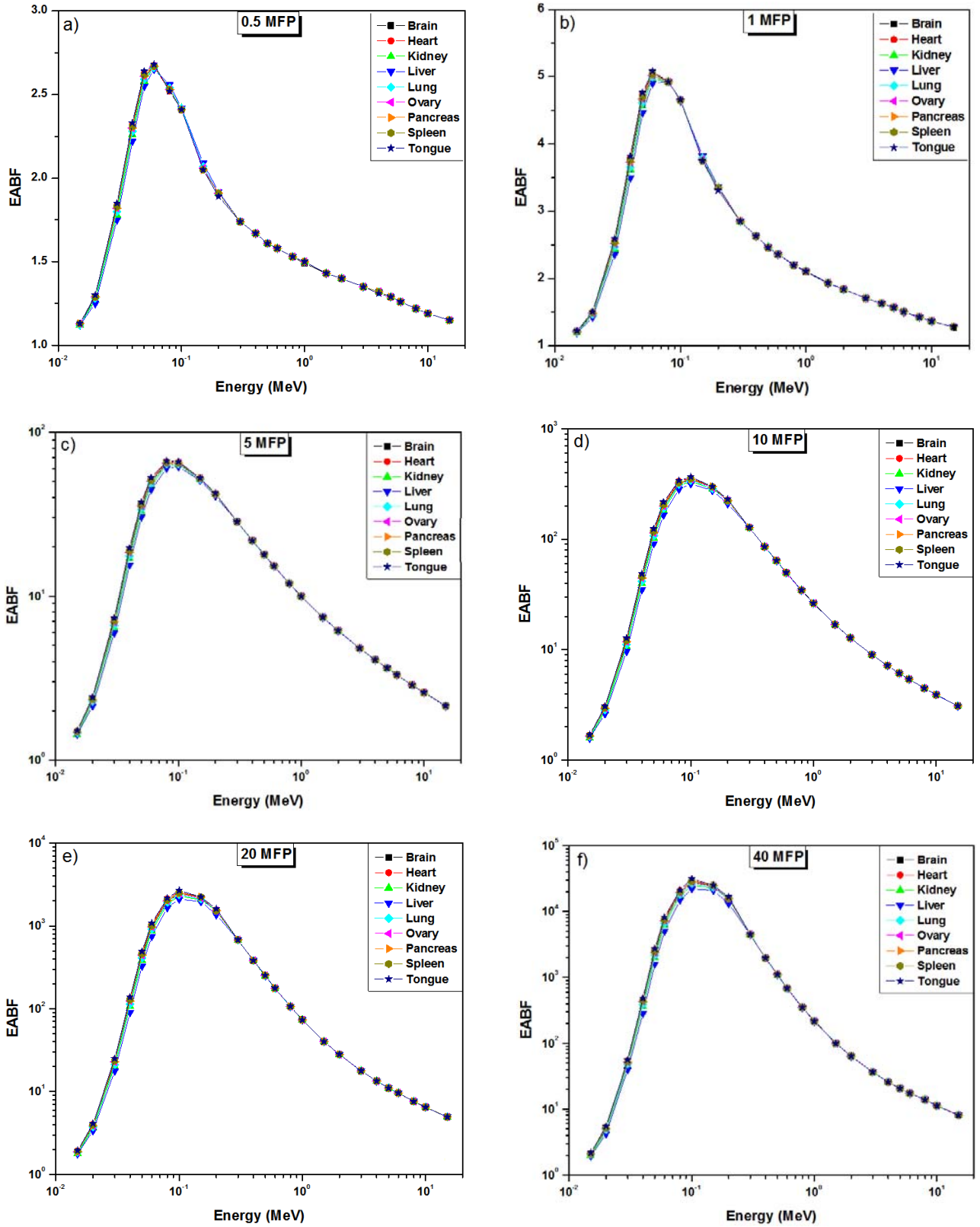


Fig. 1. Comparison of EABF versus photon energy for vital human organs at:
(a) 0.5 mfp; (b) 1 mfp; (c) 5 mfp; (d) 10 mfp; (e) 20 mfp; (f) 40 mfp

In the low energy region, the dominant photon interaction process is the photoelectric absorption, for which the atomic cross section is proportional to [$\tau \propto Z^4$ or Z^5 and $E^{-3.5}$]. In the intermediate energy region, the Compton scattering process starts dominating with linear Z dependence.

In the high-energy region, the pair production is dominant with its Z^2 dependence. Energy absorption build-up factors have 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 the photons.

The *EABF* maximum values were observed at intermediate energies, where the Compton scattering dominates. In this process, the photons are not completely removed but only their energies are degraded. Hence, this process results with more multiple scattered photons, which leads to increase in build-up of photons in the biological sample.

It is also observed that within the energy range 0.06–0.1 MeV, the *EABF* value is very high because of exclusive dominance of the Compton effect. This results in a broad peak around a particular value of incident photon energy. This implies that the contribution of secondary photons to the energy spectra has a maximum value in this energy range for the human organs.

At fixed penetration depths, *EABF* can reach values in the order of 10^4 from the values in the order of 10^0. These human organs have an equivalent atomic number, Z_{eq}, in the range of 6–8. It is observed that the *EABF* of tongue was the highest and liver was the lowest in the intermediate energy region at all the penetration depths. The smaller build-up factor can be associated with higher Z_{eq} value.

It is also observed that the organs have nearly similar values of build-up factor at lower and higher energies, because of the closeness in their Z_{eq} values (containing similar chemical compositions of elements).

The variation of *EABF* with the penetration depth is shown in Figs. 2(a)–2(d) at some selected photon energies 0.015, 0.15, 1.5 and 15 MeV. It is observed that the *EABF* increase with increasing penetration depths for the given human organs due to increase in number of scattered photons. The maximum values of the *EABF* have been obtained at the largest penetration depth (40*mfp*). The high value is due to the fact that these organs are low-*Z* materials, characterized by strong Compton scattering.

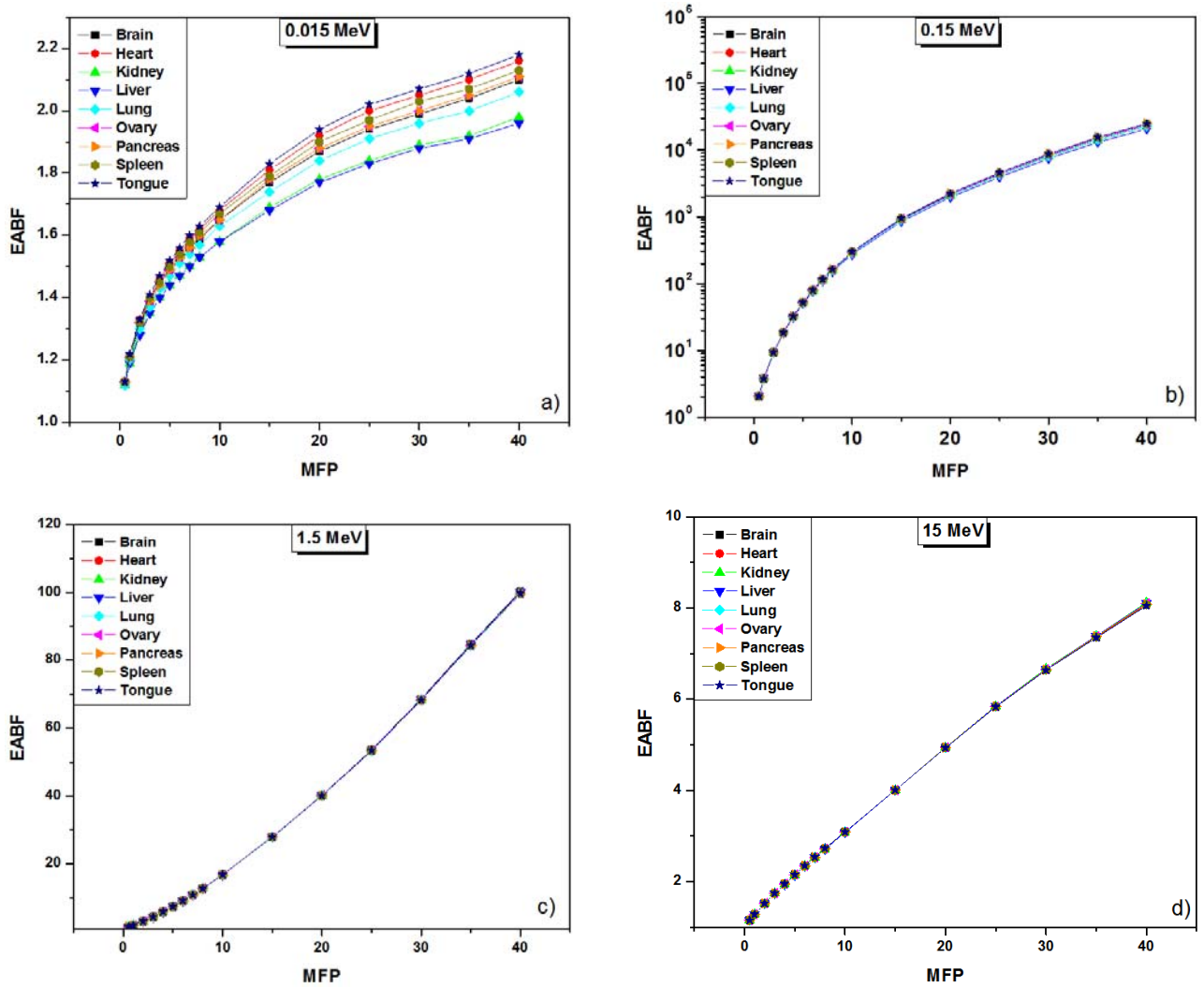


Fig. 2. Energy absorption build-up factor versus mean free path at photon energy:
(a) 0.015 MeV; (b) 0.15 MeV; (c) 1.5 MeV; (d) 15 MeV

Conclusion

The G-P fitting formula has been successfully applied for calculation of the EABF of nine vital human organs. The generated EABF has been studied as a function of incident photon energy, and penetration depth.

The EABF increases with the increase in penetration depth. It has been observed that the EABF of tongue was the highest and liver was the lowest in the intermediate energy region at all the penetration depths.

It is also determined that the biological samples have nearly similar values of build-up factor at lower and higher energies, because of the closeness in their Z_{eq} value.

The results of this study will help in estimating safe dose levels for radiotherapy patients and also will be useful in dosimetry and brachytherapy.

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