

Gamma Ray Energy Absorption Buildup Factor Computation for Human Tissues in Energy Range of Medical Radionuclides Up to 10 Mean Free Paths

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ABSTRACT

Gamma ray energy absorption buildup factors (EABF) have been meticulously computed for a comprehensive set of 16 human tissues, encompassing breast, lung, kidney, pancreas, liver, eye lens, thyroid, brain, ovary, heart, large intestine, blood, skin, spleen, muscle, and cortical bone. These calculations encompass photon energies inherent to prevalent radionuclides, spanning from 0.021 to 1.25 MeV, while delving into penetration depths reaching up to 10 mean free paths (mfp), all accomplished via the utilization of MCNPX2.6. The outcomes underscore the pivotal role of chemical composition of tissue in determining EABF, shedding light on the substantial influence this factor wields. Particularly noteworthy is the observation that cortical bone distinctly exhibits significantly lower EABF values compared to the other tissues under investigation. Leveraging the EABF values furnished in this study offers a powerful means of regulating dose levels for both therapeutic and diagnostic applications, contributing to the precise administration of radiation-based medical interventions.

Keywords: Buildup factors; Human tissues; MCNP; Gamma-ray; Photon dose

INTRODUCTION

The interaction between photons and attenuating materials results in the division of their energy spectrum into two primary components: uncollided and collided photons. The uncollided category encompasses photons that have undergone no interaction with the attenuating material. In contrast, the collided category involves photons that have experienced single or multiple scatterings, along with secondary photons like X-rays resulting from Bremsstrahlung radiation or gamma rays arising from electron-positron annihilation. According to the defined terms, the buildup factor (BF) is the ratio of the total response (combining uncollided and collided) to the uncollided response^[1].

Given that the BF is a crucial parameter in radiation shielding tasks, numerous studies have been conducted to estimate this parameter in various media, including soft tissue^[2-4], blood, bone, brain, breast, eye lens, lung, adipose tissue, muscle, and ovary^[1,5,6]. Additionally, BF estimation has been carried out for certain hydrocarbons acting as neutron moderators^[7] and for specific natural rocks^[8,9].

The BF holds critical significance not only in shield design but also in dosimetry and radiotherapy treatment plans^[10]. In medical applications, photons (Gamma and X-rays) predominantly find use in radiotherapy and diagnostic procedures, exposing various body tissues to photon radiation. Consequently, the BF of photons becomes a pivotal parameter in predicting the distribution and absorption of flux and dose within biological molecules, along with other photon interaction parameters such as mass attenuation coefficients and effective atomic numbers in biological materials^[4,5,11,12]. This understanding is crucial for assessing potential health risks and ensuring radiation doses remain within safe limits. Moreover, the buildup of photons within tissues can lead to variations in radiation dose distribution, emphasizing the need for accurate BF data^[10,13]. Thus, the acquisition of information concerning the interactions of these radiations with the body stands as an indispensable dataset for radiation safety, precise dose estimation, and reliable diagnostic and therapeutic outcomes.

Given the scarcity of prior evidence regarding the estimation of EABF for human organs and tissues within the energy range of these medical sources, it is noteworthy to mention that Manohara et al.^[5] have undertaken the calculation of gamma ray EABF for human organs and tissues relevant to radiotherapy and diagnostics using the GP-fitting method. However, it's important to note that they have not provided exact numerical values, but rather presented graphs exclusively. In the light of this context, the present article endeavors to address this knowledge gap comprehensively. The overarching objective of this study is to meticulously compute the gamma ray energy absorption buildup factor (EABF) within the energy spectrum of medical radioisotopes, encompassing diverse human organs, and extending the analysis to encompass penetration depths of up to 10 mean free paths (mfp). This effort aims to deliver valuable quantitative insights where previous data might have been limited to graphical representations.

Various methods have been developed and employed to calculate the BF, including Monte Carlo simulation^[6,14-16], G-P fitting approximation^[5,6,17-21], experimental techniques^[20,22,23], invariant embedding^[24], and the moment method^[25]. Monte Carlo N-Particle (MCNP) simulations have

been demonstrated to possess reliable capabilities in estimating the buildup factor across a broad energy range and different density materials (such as water^[16], hydrocarbons^[7]), and high-density materials like tungsten^[15]. Therefore, the calculations are conducted using the MCNPX 2.6 code. In contrast to the extensive study conducted by Yazdani Darki et al.^[26], which focused on the estimation of mass attenuation coefficients for 16 human organs across a spectrum of 10 medical radioisotopes, our research stands out for its targeted strength in exploring the gamma ray EABF. While their work provided valuable insights into mass attenuation, our study takes a focused approach to gamma ray EABF for a diverse set of 16 human tissues. This deliberate emphasis on EABF not only complements but also significantly strengthens the existing body of knowledge, providing a more detailed and comprehensive understanding of radiation interactions crucial for medical applications.

The structure of the paper is organized as follows: Section 2 extensively and transparently elaborates on the materials and methods, outlining the human organs under investigation, the energy range, and simulation geometry. Section 3 is dedicated to the validation of the simulation, followed by the presentation and discussion of results in Section 4.

MATERIALS AND METHODS

The geometry of simulation involves concentric spheres containing the materials of interest. A point isotropic sources is positioned at the center of the sphere. The radius of each sphere extends up to 10 mean free paths (mfp). To determine the average surface flux, the *F2 Tally card is employed on the surface of each sphere. The flux of uncollided particles is separated using FT and FU cards. Both photons and electrons are transported simultaneously in particle mode p,e. Both electron and photon modes were incorporated into this model, designated as mode p,e. To exclude coherent (Rayleigh) scattering and focus radiation interactions solely on Pair production, Compton (incoherent) scattering, and the photoelectric effect, the Phys:p card was implemented. Additionally, to eliminate secondary electrons generated as a result of these interactions, the Phys:e card was employed^[27].

The mean free path (mfp) of photons in the corresponding medium is the reciprocal of the total linear attenuation coefficient (μ), as defined by equation 1. The total mass attenuation coefficients are obtained from XCOM data and then converted to total attenuation using equation 2.

$$mfp = \frac{1}{\mu} \quad (1)$$

$$\mu = \rho \cdot \mu_m \quad (2)$$

BF is calculated using the following correlation:

$$BF = \frac{R_{Uncollided} + R_{Collided}}{R_{Uncollided}} = 1 + \frac{R_{Collided}}{R_{Uncollided}} \quad (3)$$

The term " $R_{Collided}$ " denotes photons that have encountered interactions (such as Compton scattering) prior to reaching the tallying surface, while " $R_{Uncollided}$ " signifies photons that successfully reached the tallying surface without any interaction. Table 1 offers details on the

composition and density of human tissues^[26,28], while Table 2 presents the mass attenuation coefficients of human tissues at the gamma energies of interest, sourced from the NIST XCOM database^[26].

Table 1: Composition and density of human tissues under study[26]

Materials	Density (g/cm ³)	Weight fraction (%)												
		H	C	N	O	Na	P	S	Cl	K	Ca	Fe	Mg	I
Breast	1.02	0.106	0.332	0.03	0.527	0.001	0.001	0.002	0.001	-	-	-	-	-
Lung	1.05	0.103	0.105	0.031	0.749	0.002	0.002	0.003	0.003	0.002	-	-	-	-
Kidney	1.05	0.103	0.132	0.03	0.724	0.002	0.002	0.002	0.002	0.002	0.001	-	-	-
Pancreas	1.04	0.106	0.169	0.022	0.694	0.002	0.002	0.001	0.002	0.002	0.001	-	-	-
Liver	1.06	0.102	0.139	0.03	0.716	0.002	0.003	0.003	0.002	0.003	-	-	-	-
Eye lens	1.07	0.096	0.195	0.057	0.646	0.001	0.001	0.003	0.001	0.002	0.001	-	-	-
Thyroid	1.05	0.104	0.119	0.024	0.746	0.002	0.001	0.001	0.002	0.001	-	-	-	0.001
Brain	1.04	0.107	0.145	0.022	0.712	0.002	0.004	0.002	0.003	0.003	-	-	-	-
Ovary	1.05	0.105	0.093	0.024	0.768	0.002	0.002	0.002	0.002	0.002	-	-	-	-
Heart	1.06	0.103	0.121	0.032	0.734	0.001	0.001	0.002	0.003	0.002	-	0.001	-	-
Large intestine	1.03	0.106	0.115	0.022	0.751	0.001	0.001	0.001	0.002	0.001	-	-	-	-
Blood	1.06	0.102	0.110	0.033	0.745	0.001	0.001	0.002	0.003	0.002	-	0.001	-	-
Skin	1.09	0.100	0.204	0.042	0.645	0.002	0.001	0.002	0.003	0.001	-	-	-	-
Spleen	1.06	0.103	0.113	0.032	0.741	0.001	0.003	0.002	0.002	0.003	-	-	-	-
Muscle (skeletal)	1.05	0.102	0.143	0.034	0.710	0.001	0.002	0.003	0.001	0.004	-	-	-	-
Cortical bone	1.95	0.034	0.165	0.042	0.435	0.001	0.103	0.003	-	-	0.225	-	0.002	-

Table 2: Mass attenuation coefficient of body tissues under study[26]

Radionuclide	Pd-103	I-125	Cs-131	Tc-99 m	Ba-133	Ir-192	Au-198	Cs-137	Ra-226	Co-60
Mean-energy (MeV)	0.021	0.029	0.030	0.140	0.218	0.380	0.412	0.663	0.830	1.25
Breast	0.6214	0.3561	0.3403	0.1525	0.1322	0.1077	0.1043	0.0852	0.07686	0.06287
Lung	0.74430	0.40180	0.38150	0.15260	0.13200	0.10740	0.10400	0.08498	0.07667	0.06271
Kidney	0.73430	0.39820	0.37820	0.15260	0.13200	0.10740	0.10400	0.08498	0.07667	0.06271
Pancreas	0.71630	0.39180	0.37250	0.15290	0.13230	0.10770	0.10430	0.08520	0.07687	0.06287
Liver	0.73920	0.39990	0.37980	0.15250	0.13180	0.10730	0.10390	0.08490	0.07660	0.06265
Eye lens	0.70280	0.38570	0.36680	0.15150	0.13110	0.10670	0.10330	0.08443	0.07617	0.06230
Thyroid	0.73320	0.39850	0.37860	0.15330	0.13220	0.10750	0.10410	0.08505	0.07673	0.06276
Brain	0.74150	0.40130	0.38110	0.15310	0.13240	0.10780	0.10440	0.08527	0.07694	0.06293
Ovary	0.73840	0.39970	0.37960	0.15290	0.13220	0.10760	0.10420	0.08513	0.07681	0.06283
Heart	0.75000	0.40440	0.38390	0.15260	0.13200	0.10740	0.10400	0.08498	0.07667	0.06271
Large intestine	0.70570	0.38750	0.36860	0.15290	0.13230	0.10770	0.10430	0.08523	0.07690	0.06289
Blood	0.73420	0.39790	0.37790	0.15250	0.13180	0.10730	0.10390	0.08491	0.07661	0.06266
Skin	0.68950	0.38100	0.36260	0.15200	0.13150	0.10710	0.10370	0.08475	0.07646	0.06254
Spleen	0.74250	0.40100	0.38070	0.15240	0.13180	0.10730	0.10390	0.08484	0.07655	0.06261
Muscle (skeletal)	0.73480	0.39830	0.37830	0.15250	0.13180	0.10730	0.10390	0.08491	0.07660	0.06265
Cortical bone	3.46000	1.44100	1.32000	0.15280	0.12630	0.10120	0.09784	0.07965	0.07180	0.05869

VALIDATION OF SIMULATION

To assess the credibility of the simulation model in computing BF values, the BFs were initially computed for water and soft tissue, then compared with published data^[16,27]. BF values calculated using the MCNP code up to 10 mfp for water and soft tissue are detailed in Table 3 and 4, respectively. These tables also include previously reported BF values. Overall, the calculated BFs exhibit substantial conformity with the published data, substantiating the precision of our simulation. Discrepancies can be ascribed to variations in Monte Carlo models and cross-section data libraries used.

Table 3: Validation of buildup factor for water and comparison with previous studies

Energy (MeV)	EABF (this study) a	EABF ^[16]	EABF ^[27]	EABF ^[5]	Relative difference (%) (b-a)/b *100	Relative difference (%) (c-a)/c *100	Relative difference (%) (d-a)/d *100
1 mfp							
0.2	3.30	3.53	3.30	--	6.60	0	--
0.5	2.53	2.61	2.57	2.47	3.25	1.55	-2.42
1	2.06	2.14	2.08	2.11	3.83	0.96	2.36
2	1.71	1.73	1.73	--	-0.20	1.15	--
2 mfp							
0.2	7.41	7.44	7.45	--	0.39	0.53	--
0.5	4.99	4.95	5.09	4.84	-0.76	1.96	-3.09
1	3.54	3.6	3.60	3.59	1.76	1.66	1.39
2	2.54	2.3	2.58	--	-10.59	1.55	--
4 mfp							
0.2	22.79	25	24.10	--	8.81	5.43	--
0.5	12.71	12.5	12.82	12.40	-1.74	0.85	-2.5
1	7.35	7.21	7.61	7.54	-2.00	3.41	2.51
2	4.37	4.75	4.58	--	7.89	4.58	--
7 mfp							
0.2	74.37	66	79.21	--	-12.69	6.11	--
0.5	33.14	31	31.00	31.97	-6.92	-6.90	-3.65
1	15.34	14.5	15.53	15.68	-5.86	1.22	2.16
2	7.89	6.36	7.74	--	-24.19	-1.93	--
10 mfp							
0.2	175.67	157	201.48	--	-11.89	12.81	--
0.5	66.24	60	70.3	62.57	-10.41	5.77	-5.86
1	26.92	23	27.5	26.16	-17.06	2.10	-2.90
2	11.75	9.15	11.76	--	-28.47	0.08	--

Table 4: Validation of buildup factor for soft tissue and comparison with previous studies

Energy (MeV)	EABF (this study) a	EABF ^[16]	EABF ^[27]	Relative difference (%) (b-a)/b *100	Relative difference (%) (c-a)/c *100
1 mfp					
0.2	3.27	3.24	3.32	-0.98	1.50
0.5	2.53	2.50	2.56	-1.04	1.17
1	2.06	2.04	2.08	-0.91	0.96
2	1.71	1.70	1.73	-0.79	1.15
2 mfp					
0.2	7.33	7.39	7.51	0.69	2.39
0.5	5.00	4.9	5.07	-2.11	1.38
1	3.53	3.5	3.58	-1.12	1.39
2	2.54	2.5	2.57	-1.80	1.16
4 mfp					
0.2	22.69	23	24.20	1.35	6.23

0.5	12.81	12.7	12.92	0.90	0.85
1	7.37	7.2	7.34	2.39	-0.40
2	4.37	4.5	4.60	2.80	5.00
7 mfp					
0.2	72.90	80	77.18	8.87	5.54
0.5	33.27	32	29.00	-3.97	-14.72
1	15.43	14.5	15.02	-6.45	-2.72
2	7.91	7.3	7.48	-8.38	-5.74
10 mfp					
0.2	178.15	183	198.01	2.65	10.02
0.5	67.14	61.1	74.24	-9.89	9.56
1	27.16	23	28.82	-18.10	5.75
2	11.80	11.1	11.36	-6.39	-3.87

RESULTS AND CONCLUSION

Tables 5 to 20 present the calculated energy absorption buildup factors (EABF) for the selected human tissues. Each table provides EABF values corresponding to specific gamma energies of medically relevant radionuclides, considering penetration depths up to 10 mfp.

Table 5: Gamma EABF for breast tissue

Radionuclide	Energy (MeV)	1 mfp	2 mfp	4 mfp	7 mfp	10 mfp
Pd-103	0.021	1.41	1.65	2.01	2.47	2.84
I-125	0.029	1.90	2.64	3.93	5.88	7.94
Cs-131	0.030	1.97	2.79	4.26	6.64	8.90
Tc-99 m	0.140	3.55	8.18	26.03	87.43	218.62
Ba-133	0.218	3.23	7.24	22.45	71.95	176.28
Ir-192	0.380	2.75	5.75	15.93	45.04	96.85
Au-198	0.412	2.69	5.53	15.04	41.80	87.37
Cs-137	0.663	2.33	4.37	10.37	24.94	47.26
Ra-226	0.830	2.18	3.91	8.62	19.34	34.92
Co-60	1.25	1.94	3.19	6.23	12.25	20.56

Table 6: Gamma EABF for lung tissue

Radionuclide	Energy (MeV)	1 mfp	2 mfp	4 mfp	7 mfp	10 mfp
Pd-103	0.021	1.32	1.50	1.75	2.07	2.28
I-125	0.029	1.73	2.27	3.15	4.44	5.55
Cs-131	0.030	1.79	2.38	3.40	4.88	6.20
Tc-99 m	0.140	3.47	7.83	23.92	75.96	184.13
Ba-133	0.218	3.19	7.03	21.15	65.66	156.52
Ir-192	0.380	2.74	5.64	15.36	42.50	90.32
Au-198	0.412	2.67	5.44	14.47	39.60	81.90
Cs-137	0.663	2.32	4.32	10.12	24.11	45.52
Ra-226	0.830	2.17	3.86	8.45	18.79	33.93
Co-60	1.25	1.93	3.16	6.14	12.06	20.17

Table 7: Gamma EABF for kidney tissue

Radionuclide	Energy (MeV)	1 mfp	2 mfp	4 mfp	7 mfp	10 mfp
Pd-103	0.021	1.32	1.51	1.77	2.10	2.30
I-125	0.029	1.74	2.29	3.20	4.54	5.65
Cs-131	0.030	1.80	2.41	3.47	4.98	6.35
Tc-99 m	0.140	3.48	7.85	24.05	76.72	186.09
Ba-133	0.218	3.19	7.05	21.22	66.00	157.44
Ir-192	0.380	2.74	5.65	15.39	42.63	90.61
Au-198	0.412	2.67	5.44	14.50	39.73	82.35
Cs-137	0.663	2.32	4.32	10.13	24.17	45.58
Ra-226	0.830	2.17	3.86	8.46	18.83	33.98
Co-60	1.25	1.93	3.16	6.15	12.08	20.17

Table 8: Gamma EABF for Pancreas tissue

Radionuclide	Energy (MeV)	1 mfp	2 mfp	4 mfp	7 mfp	10 mfp
Pd-103	0.021	1.33	1.53	1.80	2.14	2.37
I-125	0.029	1.76	2.34	3.30	4.75	5.90
Cs-131	0.030	1.82	2.47	3.55	5.21	6.65
Tc-99 m	0.140	3.49	7.90	24.39	78.50	190.03
Ba-133	0.218	3.20	7.08	21.39	66.86	160.81
Ir-192	0.380	2.74	5.66	15.44	42.92	91.60
Au-198	0.412	2.68	5.45	14.62	39.99	82.70
Cs-137	0.663	2.32	4.33	10.17	24.28	45.84
Ra-226	0.830	2.17	3.87	8.47	18.91	34.15
Co-60	1.25	1.93	3.16	6.16	12.10	20.22

Table 9: Gamma EABF for Liver tissue

Radionuclide	Energy (MeV)	1 mfp	2 mfp	4 mfp	7 mfp	10 mfp
Pd-103	0.021	1.32	1.50	1.76	2.08	2.28
I-125	0.029	1.73	2.28	3.17	4.49	5.58
Cs-131	0.030	1.79	2.40	3.42	4.93	6.30
Tc-99 m	0.140	3.48	7.84	23.82	76.23	185.02
Ba-133	0.218	3.19	7.04	21.09	65.70	157.28
Ir-192	0.380	2.74	5.64	15.37	42.53	90.37
Au-198	0.412	2.67	5.44	14.49	39.62	82.10
Cs-137	0.663	2.32	4.32	10.12	24.12	45.55
Ra-226	0.830	2.17	3.86	8.46	18.79	33.95
Co-60	1.25	1.93	3.16	6.14	12.07	20.16

Table 10: Gamma EABF for eye-lens tissue

Radionuclide	Energy (MeV)	1 mfp	2 mfp	4 mfp	7 mfp	10 mfp
Pd-103	0.021	1.34	1.54	1.81	2.16	2.37
I-125	0.029	1.77	2.36	3.32	4.74	6.05
Cs-131	0.030	1.83	2.48	3.60	5.27	6.75
Tc-99 m	0.140	3.49	7.92	24.46	78.99	191.90
Ba-133	0.218	3.20	7.09	21.41	67.26	161.91

Ir-192	0.380	2.74	5.67	15.46	43.21	91.87
Au-198	0.412	2.68	5.47	14.65	40.17	83.27
Cs-137	0.663	2.32	4.33	10.20	24.32	45.93
Ra-226	0.830	2.17	3.87	8.49	18.94	34.26
Co-60	1.25	1.93	3.17	1.93	3.17	20.25

Table 11: Gamma EABF for thyroid tissue

Radionuclide	Energy (MeV)	1 mfp	2 mfp	4 mfp	7 mfp	10 mfp
Pd-103	0.021	1.32	1.51	1.77	2.10	2.30
I-125	0.029	1.74	2.29	3.19	4.49	5.69
Cs-131	0.030	2.79	2.41	3.47	4.97	6.39
Tc-99 m	0.140	3.39	7.45	21.71	65.04	152.62
Ba-133	0.218	3.15	6.80	19.64	58.43	136.84
Ir-192	0.380	2.71	5.52	14.61	39.77	83.12
Au-198	0.412	2.65	5.32	15.41	37.10	76.19
Cs-137	0.663	2.30	4.25	9.83	23.18	43.55
Ra-226	0.830	2.16	3.81	8.23	18.22	32.77
Co-60	1.25	1.92	3.13	6.04	11.86	19.80

Table 12: Gamma BF for brain tissue

Radionuclide	Energy (MeV)	1 mfp	2 mfp	4 mfp	7 mfp	10 mfp
Pd-103	0.021	1.32	1.50	1.76	2.08	2.29
I-125	0.029	1.73	2.28	3.18	4.50	5.60
Cs-131	0.030	1.79	2.40	3.44	4.93	6.30
Tc-99 m	0.140	3.48	7.84	23.87	76.34	184.47
Ba-133	0.218	3.19	7.04	21.07	65.69	157.32
Ir-192	0.380	2.74	5.64	15.34	42.51	90.27
Au-198	0.412	2.67	5.44	14.47	39.52	81.73
Cs-137	0.663	2.32	4.32	10.13	24.11	45.44
Ra-226	0.830	2.17	3.86	8.45	18.78	34.28
Co-60	1.25	1.93	3.16	6.14	12.07	20.26

Table 13: Gamma EABF for ovary tissue

Radionuclide	Energy (MeV)	1 mfp	2 mfp	4 mfp	7 mfp	10 mfp
Pd-103	0.021	1.32	1.51	1.76	2.09	2.28
I-125	0.029	1.74	2.28	3.18	4.46	5.63
Cs-131	0.030	1.80	2.40	3.43	4.95	6.33
Tc-99 m	0.140	3.48	7.85	23.95	76.90	186.36
Ba-133	0.218	3.19	7.05	21.16	66.03	158.26
Ir-192	0.380	2.74	5.65	15.37	42.61	90.81
Au-198	0.412	2.67	5.44	14.56	39.70	82.25
Cs-137	0.663	2.32	4.32	10.13	24.16	45.64
Ra-226	0.830	2.17	3.87	8.46	18.83	34.00
Co-60	1.25	1.93	3.16	6.15	12.08	20.18

Table 14: Gamma EABF for heart tissue

Radionuclide	Energy (MeV)	1 mfp	2 mfp	4 mfp	7 mfp	10 mfp
Pd-103	0.021	1.31	1.49	1.74	2.05	2.25
I-125	0.029	1.72	2.25	3.12	4.39	5.43
Cs-131	0.030	1.78	2.37	3.37	4.80	6.09
Tc-99 m	0.140	3.47	7.81	23.66	75.33	181.25
Ba-133	0.218	3.19	7.01	21.00	65.12	155.02
Ir-192	0.380	2.73	5.63	15.25	42.24	89.73
Au-198	0.412	2.67	5.43	14.46	39.40	81.52
Cs-137	0.663	2.32	4.31	10.11	24.02	45.35
Ra-226	0.830	2.17	3.86	8.43	18.74	33.85
Co-60	1.25	1.93	3.16	6.14	12.05	20.15

Table 15: Gamma EABF for large intestine tissue

Radionuclide	Energy (MeV)	1 mfp	2 mfp	4 mfp	7 mfp	10 mfp
Pd-103	0.021	1.34	1.54	1.81	2.17	2.39
I-125	0.029	1.77	2.36	3.33	4.77	6.07
Cs-131	0.030	1.83	2.49	3.60	5.26	6.84
Tc-99 m	0.140	3.49	7.93	24.46	79.32	192.84
Ba-133	0.218	3.20	7.09	21.54	67.41	162.75
Ir-192	0.380	2.79	5.81	16.07	45.00	92.13
Au-198	0.412	2.68	5.46	14.63	40.19	83.40
Cs-137	0.663	2.32	4.33	10.21	24.40	46.06
Ra-226	0.830	2.17	3.87	8.49	18.95	34.29
Co-60	1.25	1.93	3.17	6.17	12.11	20.27

Table 16: Gamma EABF for blood tissue

Radionuclide	Energy (MeV)	1 mfp	2 mfp	4 mfp	7 mfp	10 mfp
Pd-103	0.021	1.32	1.50	1.75	2.09	2.30
I-125	0.029	1.73	2.26	3.12	4.41	5.42
Cs-131	0.030	1.79	2.38	3.37	4.84	6.09
Tc-99 m	0.140	3.47	7.79	23.56	74.67	180.71
Ba-133	0.218	3.19	7.01	20.92	64.85	155.08
Ir-192	0.380	2.73	5.63	15.29	42.24	89.45
Au-198	0.412	2.67	5.43	14.41	39.34	81.33
Cs-137	0.663	2.32	4.31	10.09	24.01	45.39
Ra-226	0.830	2.17	3.86	8.43	18.73	33.83
Co-60	1.25	1.93	3.16	6.13	12.03	20.15

Table 17: Gamma EABF for skin tissue

Radionuclide	Energy (MeV)	1 mfp	2 mfp	4 mfp	7 mfp	10 mfp
Pd-103	0.021	1.35	1.55	1.84	2.21	2.43
I-125	0.029	1.79	2.40	3.42	4.89	6.35
Cs-131	0.030	1.85	2.53	3.70	5.45	7.10
Tc-99 m	0.140	3.50	7.97	24.63	80.42	196.40
Ba-133	0.218	3.21	7.12	21.63	68.02	164.28

Ir-192	0.380	2.74	5.68	15.60	43.60	92.74
Au-198	0.412	2.68	5.48	14.73	40.40	84.23
Cs-137	0.663	2.32	4.34	10.23	24.47	46.21
Ra-226	0.830	2.17	3.88	8.51	19.01	34.34
Co-60	1.25	1.94	3.17	6.18	12.14	20.30

Table 18: Gamma EABF for spleen tissue

Radionuclide	Energy (MeV)	1 mfp	2 mfp	4 mfp	7 mfp	10 mfp
Pd-103	0.021	1.32	1.50	1.75	2.07	2.27
I-125	0.029	1.73	2.27	3.16	4.46	5.58
Cs-131	0.030	1.79	2.39	3.41	4.89	6.22
Tc-99 m	0.140	3.48	7.85	24.01	76.70	185.18
Ba-133	0.218	3.19	7.05	21.13	65.81	156.54
Ir-192	0.380	2.74	5.65	15.40	42.81	90.47
Au-198	0.412	2.68	5.45	14.52	39.83	82.06
Cs-137	0.663	2.32	4.33	10.15	24.16	45.65
Ra-226	0.830	2.17	3.87	8.46	18.86	33.89
Co-60	1.25	1.93	3.17	6.16	12.12	20.10

Table 19: Gamma EABF for Muscle tissue

Radionuclide	Energy (MeV)	1 mfp	2 mfp	4 mfp	7 mfp	10 mfp
Pd-103	0.021	1.32	1.51	1.76	2.09	2.30
I-125	0.029	1.74	2.29	3.19	4.52	5.64
Cs-131	0.030	1.80	2.41	3.46	5.01	6.35
Tc-99 m	0.140	3.48	7.84	23.99	76.58	185.76
Ba-133	0.218	3.19	7.05	21.17	65.95	157.74
Ir-192	0.380	2.74	5.65	15.36	42.73	90.43
Au-198	0.412	2.67	5.44	14.55	39.67	82.21
Cs-137	0.663	2.32	4.32	10.15	24.16	45.62
Ra-226	0.830	2.17	3.86	8.45	18.81	34.01
Co-60	1.25	1.93	3.16	6.15	12.08	20.20

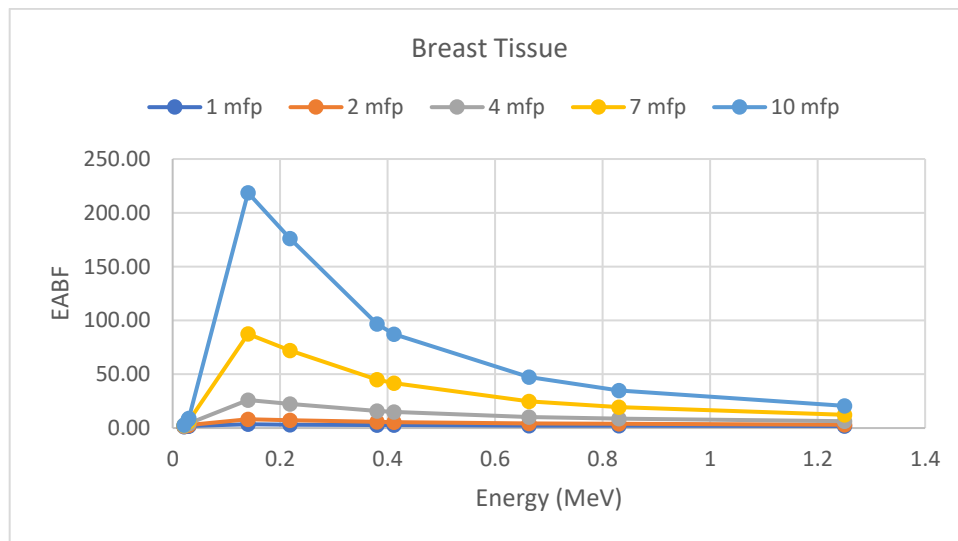
Table 20: Gamma EABF for cortical bone tissue

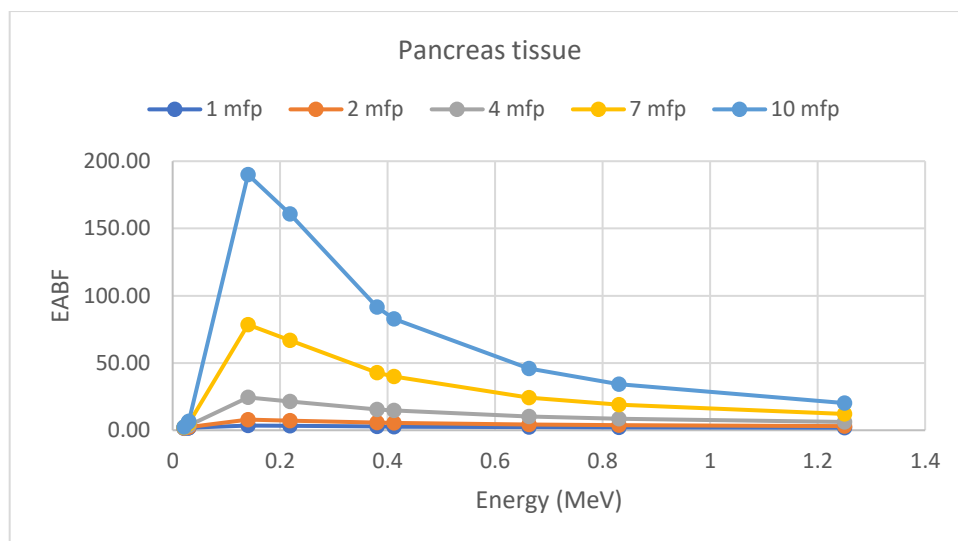
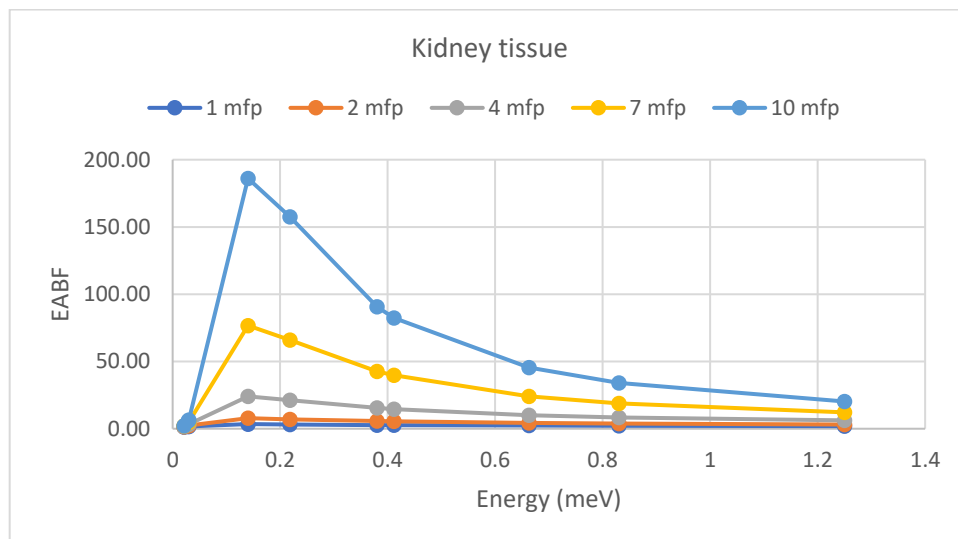
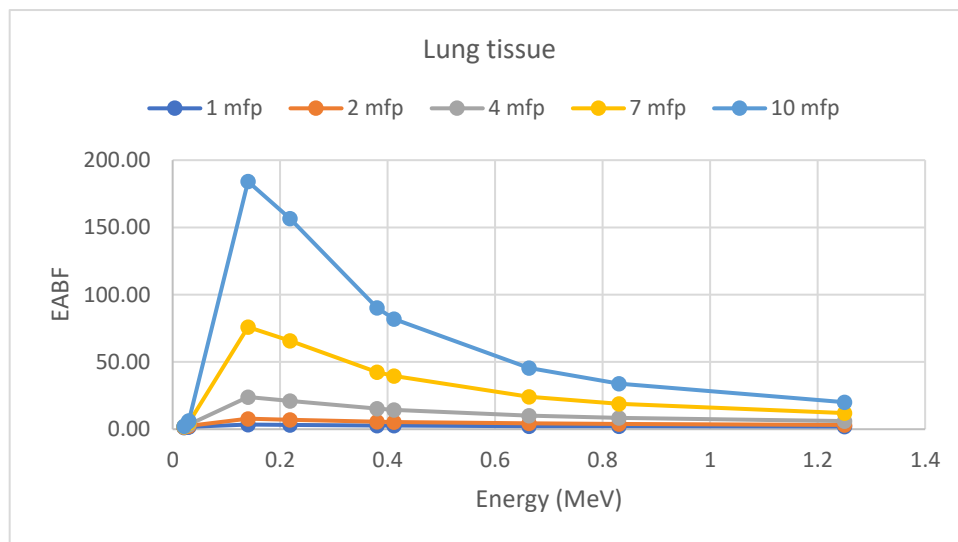
Radionuclide	Energy (MeV)	1 mfp	2 mfp	4 mfp	7 mfp	10 mfp
Pd-103	0.021	1.05	1.07	1.10	1.12	1.13
I-125	0.029	1.12	1.18	1.26	1.36	1.41
Cs-131	0.030	1.14	1.20	1.29	1.40	1.45
Tc-99 m	0.140	2.70	4.75	9.93	21.62	39.10
Ba-133	0.218	2.75	5.12	11.70	27.89	55.47
Ir-192	0.380	2.51	4.64	10.74	25.56	50.97
Au-198	0.412	2.47	4.54	10.43	24.55	48.72
Cs-137	0.663	2.20	3.82	8.19	18.27	33.81
Ra-226	0.830	2.07	3.49	7.13	15.09	27.22
Co-60	1.25	1.87	2.94	5.53	10.65	17.70

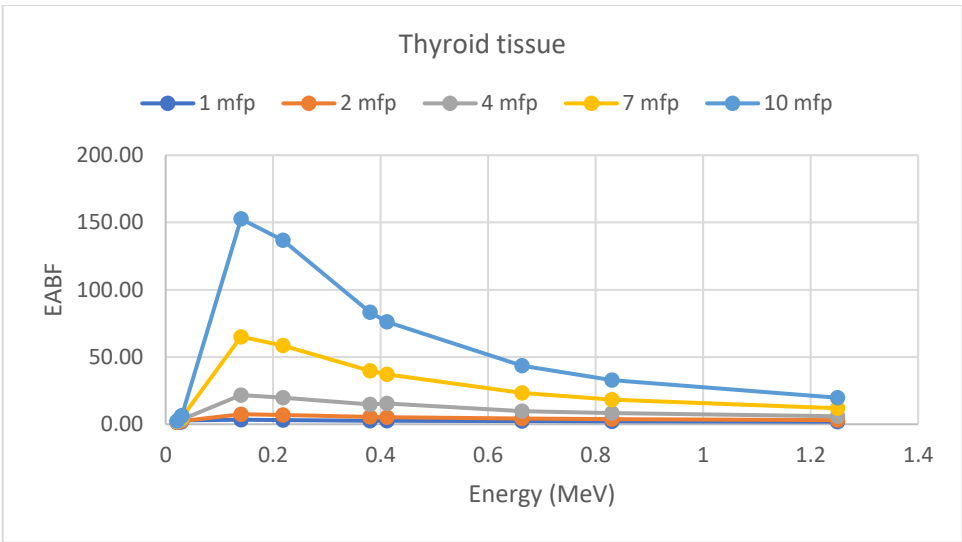
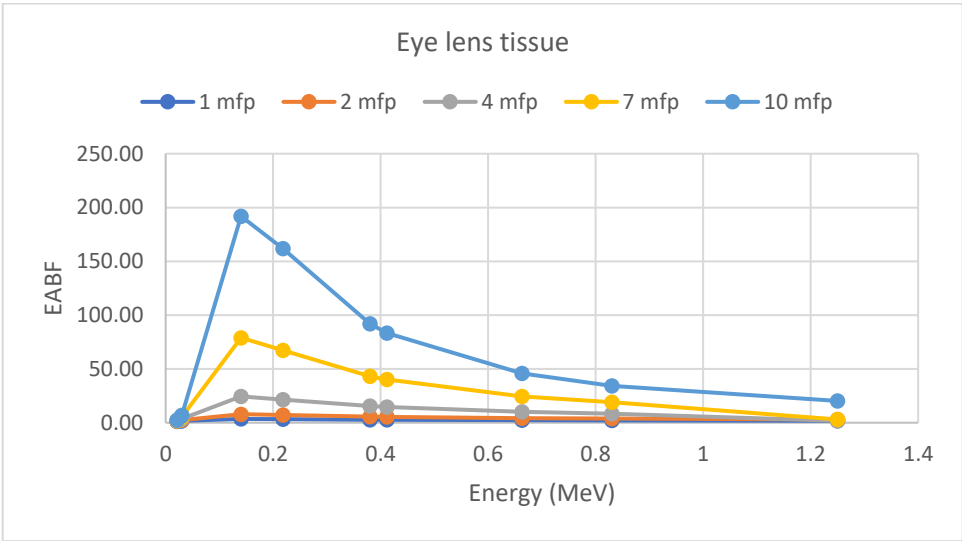
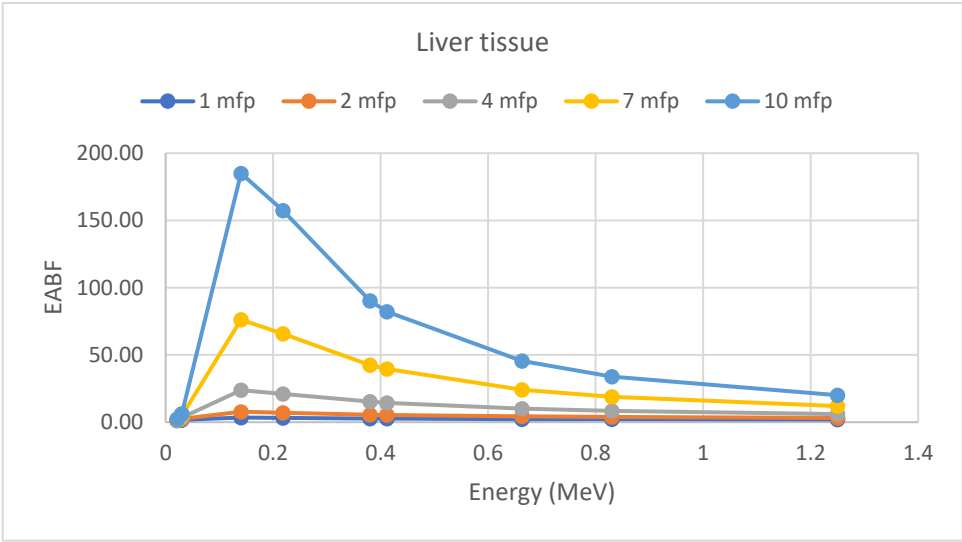
Across all examined materials except cortical bone, the highest EABF is achieved at the gamma energy of the Tc-99m radionuclide (0.14 MeV). This phenomenon results from the prevalence of multiple Compton scatterings, which are the dominant interactions at this energy range (0.14 MeV). Notably elevated BF values characterize the Compton scattering region^[1,6]. Above this energy threshold, the growing significance of pair production gradually reduces the EABF as photon energy increases. Pair production leads to the removal of one photon, giving rise to the production of an electron-positron pair.

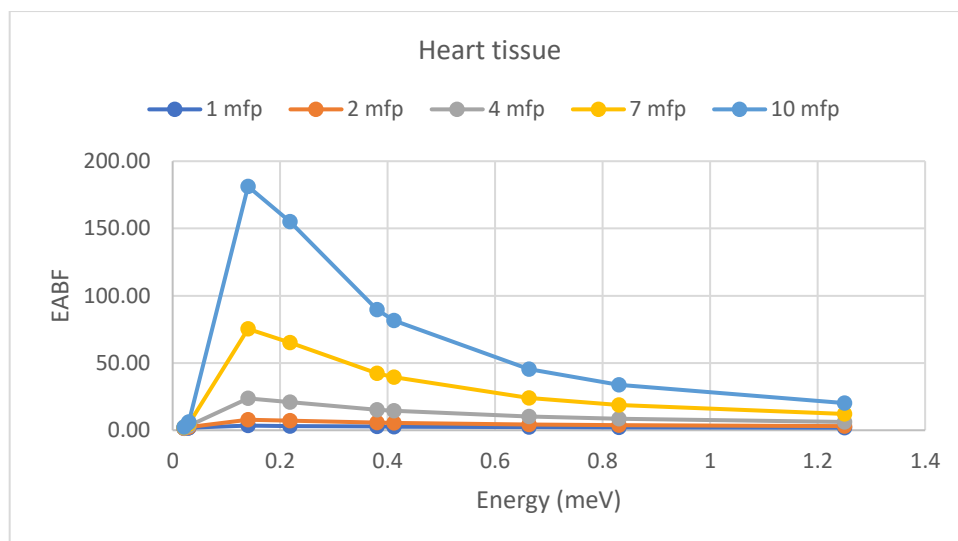
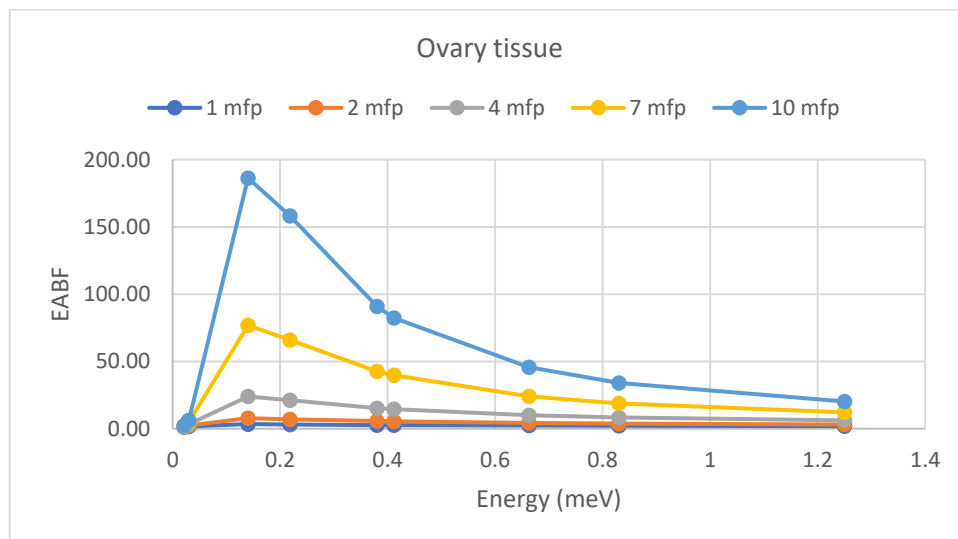
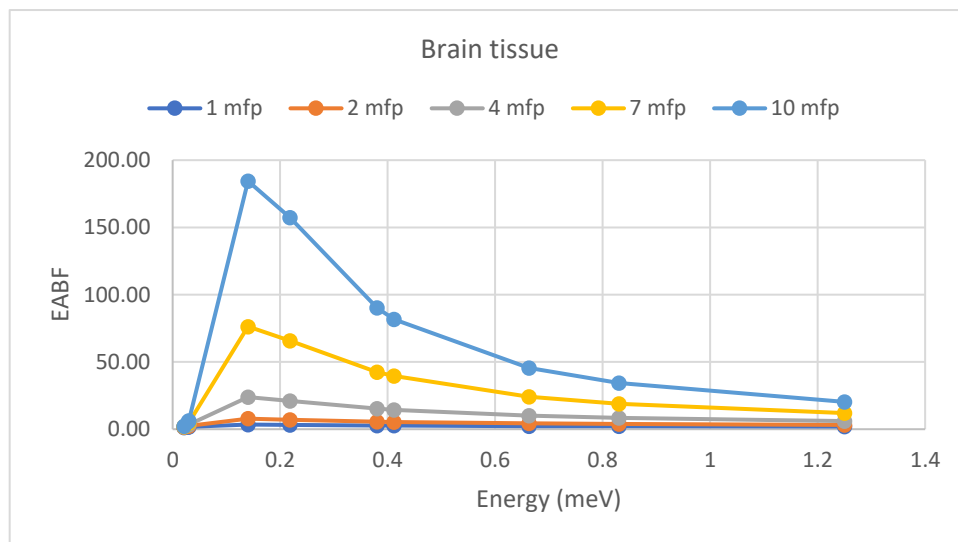
Consequently, fewer photons persist within the medium, causing the BF to decline. Cortical bone primarily consists of high-Z materials like calcium (Ca) and phosphorus (P), in contrast to other tissues predominantly composed of low-Z materials such as hydrogen (H) and oxygen (O). Consequently, the EABF for cortical bone reaches its peak at a higher energy level (0.218 MeV) compared to other tissue materials. Additionally, the maximum EABF for cortical bone generally remains lower than the peak observed for other tissues across all thicknesses.

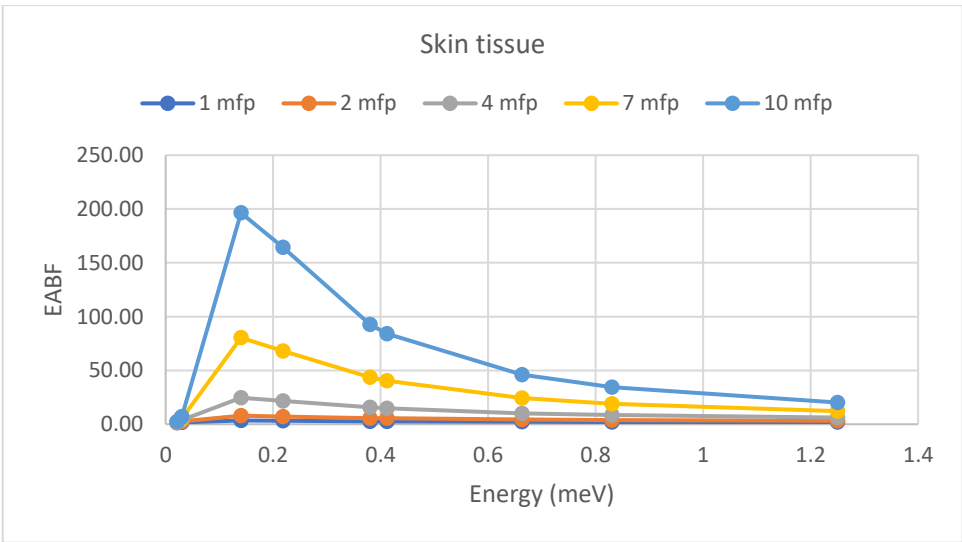
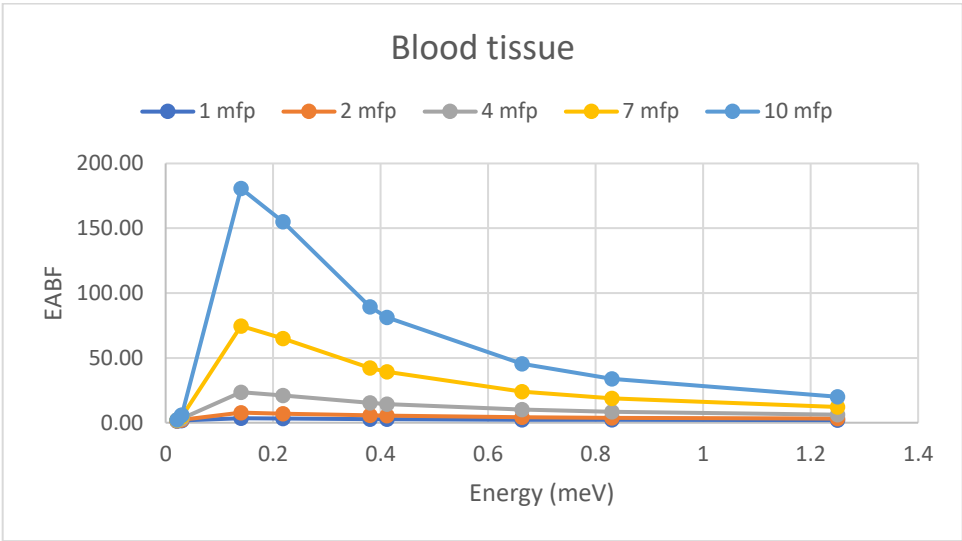
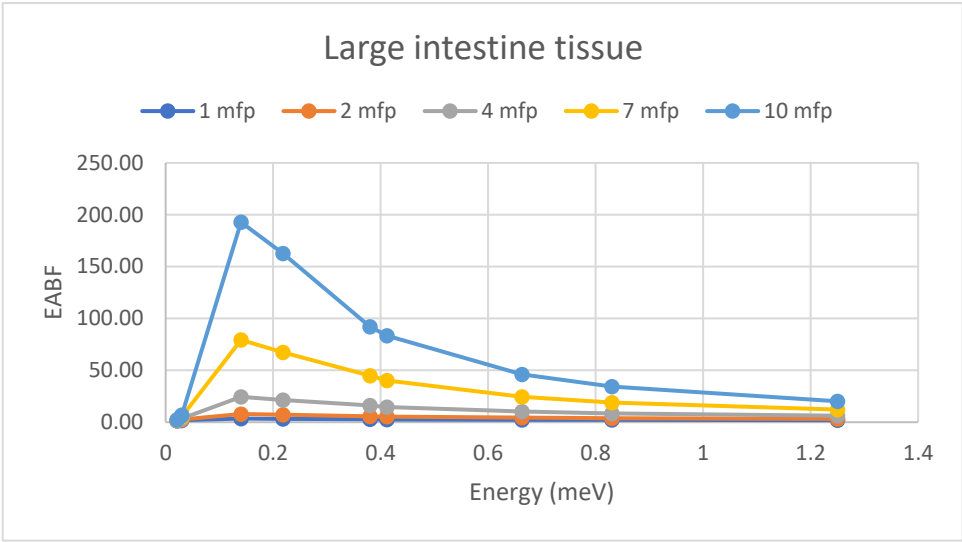
Figure 1 visually illustrates the trend of EABF, showcasing the highest value for breast tissue and the lowest for cortical bone. This phenomenon is consistent with findings from other studies as well^[5,6]. This contrast can be explained by considering the equivalent atomic number (Z_{eq}) of the compound. Breast tissue, characterized by a low Z_{eq} , contrasts with cortical bone where medium-Z elements carry a higher weight fraction.











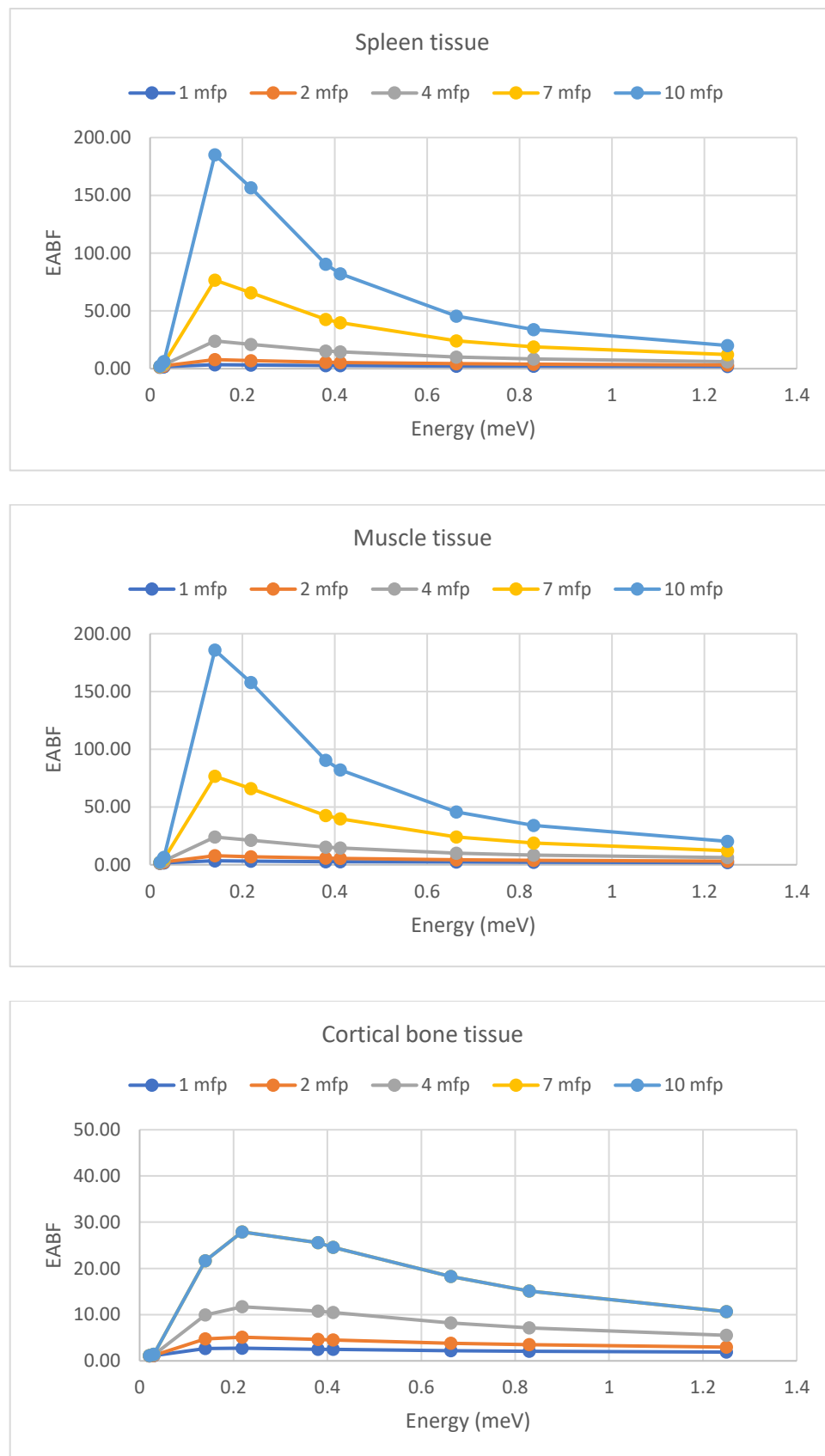


Figure 1: Variation of EABF with energy for investigated penetration depths

Figures 1 to 16 collectively demonstrate that EABF escalates with increasing penetration depth. A larger penetration depth indicates a higher number of scattering events, thereby yielding higher EABF values. Moreover, we successfully calculated the EABF for the human tissues, extending our analysis across the energy spectrum of common medical radionuclides. The validity of our values is substantiated through meticulous validation of our simulations against existing literature data, specifically for water and soft tissues. This validation process ensures the reliability and accuracy of our calculated EABF values, allowing for informed and confident utilization of the results in medical applications, radiation safety considerations, and treatment planning.

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