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Computation of exposure build-up factors in teeth

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ABSTRACT

The G-P fitting method has been used to compute the exposure build-up factor of teeth [enamel outer surface (EOS), enamel middle (EM), enamel dentin junction towards enamel (EDJE), enamel dentin junction towards dentin (EDJD), dentin middle (DM) and dentin inner surface (DIS)] for a wide energy range (0.015–15 MeV) up to the penetration depth of 40 mean free paths. The dependence of exposure build-up factor on incident photon energy, penetration depth, electron density and effective atomic number has also been studied. The computed exposure build-up factor is useful to estimate the relative dose distribution in different regions of teeth.

1. Introduction

When photons enter the medium/body, they degrade their energy and build up in the medium, giving rise to secondary radiation, which can be estimated by a factor called the 'build-up factor'. Calculations of the energy absorbed in a medium include not only the contribution of uncollided photons from the source, but must also include contributions from collided and secondary photons. In practice, this is done by multiplying the contribution of uncollided photons with the energy absorption build-up factor (Harima, 1993; Shultis and Faw, 2005). The energy absorption build-up factor is the ratio of the total energy absorbed due to uncollided, collided and secondary photons to the energy absorbed due to only uncollided photons. The energy absorption build-up factor is also defined as the build-up factor in which the quantity of interest is absorbed or deposited energy in the interacting material and the detector response function is that of absorption in the interacting medium, whereas the exposure build-up factor is defined as that build-up factor in which the quantity of interest is exposure and the detector response function is that of absorption in air. The build-up factor is an important parameter in the distribution of photon flux in every object. In brachytherapy, radioactive seeds are planted in the patient's body to destroy the cancer tumor (Chibani, 2005; Tsiakalos, 2006). Thus it is important to consider the photon build-up factor in the calculation of radiation dose received by the cancer cells.

The build-up factor data were computed by different codes such as PALLAS-PL (Takeuchi, 1973), RADHEAT-V4 (Yamano et al., 1989), ADJMOM-1 (Simmons, 1973) and ASFIT (Gopinath and Samthanam, 1971). Several authors have provided different build-up factor data for extensive utilization of design in radiation shields and for other purposes (Hubbell, 1963; Chilton et al., 1980; Harima, 1983; Sakamoto et al., 1988; Brar et al., 1994; Brar and Mudahar, 1995). American National Standard (ANS) (1991) ANSI/ANS 6.4.3 used the G-P fitting method and provided build-up factor data for 23 elements, water, air and concrete at 25 standard energies in the energy range 0.015–15 MeV with suitable interval up to the penetration depth of 40 mean free path. Earlier works (Harima et al., 1986) compared computed build-up factors using the G-P fitting method with the PALLAS code. Good agreement was observed for penetration depth up to 40 mean free path. Shimizu et al. (2004) compared the build-up factors obtained by three different methods (G-P fitting, invariant embedding and Monte Carlo method) and only small discrepancies were observed for low-*Z* elements up to 10 mean free path.

Singh et al. (2008) studied the variation of energy absorption build-up factors with incident photon energy and penetration depth for some solvents. Sidhu et al. (2000) computed the exposure build-up factors in biological samples and studied the variation of exposure build-up factors with incident photon energy and effective atomic number.

In the present work an attempt has been made to compute exposure build-up factors for different regions of teeth such as enamel outer surface (EOS), enamel middle (EM), enamel dentin junction towards enamel (EDJE), enamel dentin junction towards dentin (EDJD), dentin middle (DM) and dentin inner surface (DIS) for a wide energy range (0.015–15 MeV) up to the penetration depth of 40 mean free path using the G-P fitting method. Such data will be of prime importance in medical dosimetry.

2. Present work

Computations of the exposure build-up factor have been divided into three parts, which are as follows.

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2.1. Computation of effective atomic number

Theoretical values for the mass attenuation coefficient can be found in the tabulation by Hubbell and Seltzer (1995). Instead of interpolating tabulated values and using the mixture rule, some computer programs such as WinXCom or its predecessor XCOM can save a lot of manual work and time. The XCOM program was originally developed by Berger and Hubbell (1987) for calculating mass attenuation coefficients or photon interaction cross sections for any element, compound or mixture in the energy range 1 keV–100 GeV. Later, this well known and widely used program was enhanced and transformed to the Windows platform by Gerward et al. (2001, 2004) under the name WinXCom. All computations in the present work have been carried out using the program WinXCom. The chemical composition of teeth was analyzed with characteristic X-ray energy dispersive spectroscopy (Pilar et al., 2003), and is given in Table 1.

The molecular cross section has been estimated using the equation

$$\sigma_m = \frac{1}{N}\left(\frac{\mu}{\rho}\right)_{bio}\sum_i n_i A_i \tag{1}$$

where n_i is the number of atoms of the ith element in a given molecule, $(\mu/\rho)_{bio}$ the mass attenuation coefficient of the bio molecule, N the Avogadro number and A_i the atomic weight of the element i. $(\mu/\rho)_{bio}$ was estimated based on the chemical composition of teeth. The atomic cross section is estimated using the equation

$$\sigma_a = \frac{\sigma_m}{\sum_i n_i} \tag{2}$$

The electronic cross section is estimated using the equation

$$\sigma_e = \frac{1}{N}\sum_i \left(\frac{f_i A_i}{Z_i}\right)\left(\frac{\mu}{\rho}\right)_i \tag{3}$$

where f_i is the fractional abundance (a mass fraction of the ith element in the molecule) and Z_i the atomic number of the ith element in a molecule. Finally Z_{eff} is estimated as

$$Z_{eff} = \frac{\sigma_a}{\sigma_e} \tag{4}$$

The effective electron density (N_{el}) expressed as the number of electrons per unit mass is closely related to the effective atomic number, which is calculated by the following equation:

$$N_{el} = \frac{N}{\sum_i n_i A_i} Z_{eff} \sum_i n_i \tag{5}$$

Table 1
Composition of teeth enamel and dentin.

Element	EOS>	EM	EDJE	EDJD	DM	DIS
C	0.3859	0.3628	0.3705	0.59	0.5227	0.4984
O	0.3259	0.3421	0.3451	0.3067	0.3057	0.3354
Na	0.0024	0.0044	0.0066	0.0047	0.0042	0.0036
Mg	0.0016	0.0023	0.0022	0.0025	0.0034	0.0045
P	0.1067	0.1086	0.1046	0.0441	0.0623	0.0632
Cl	0.1063	0.0025	0.0009	–	–	–
Ca	0.1736	0.1774	0.1699	0.0519	0.0915	0.095

EOS—enamel outer surface, EM—enamel middle, EDJE—enamel dentin junction towards enamel, EDJD—enamel dentin junction towards dentin, DM—dentin middle and DIS—dentin inner surface.

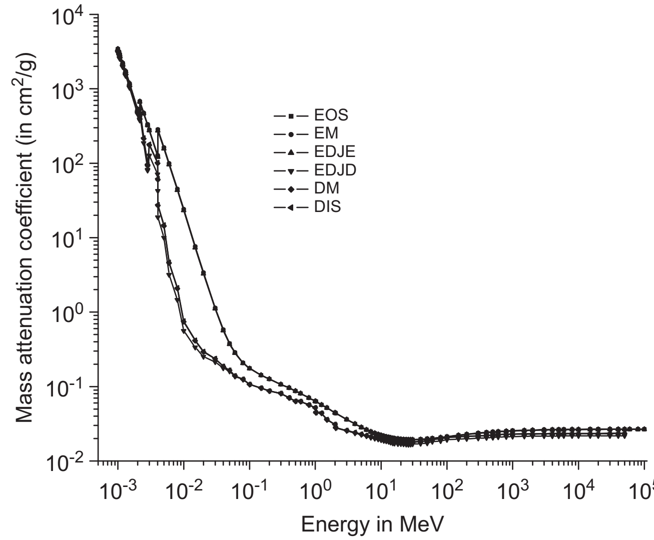

Fig. 1. Variation of mass attenuation coefficients with photon energy for teeth.

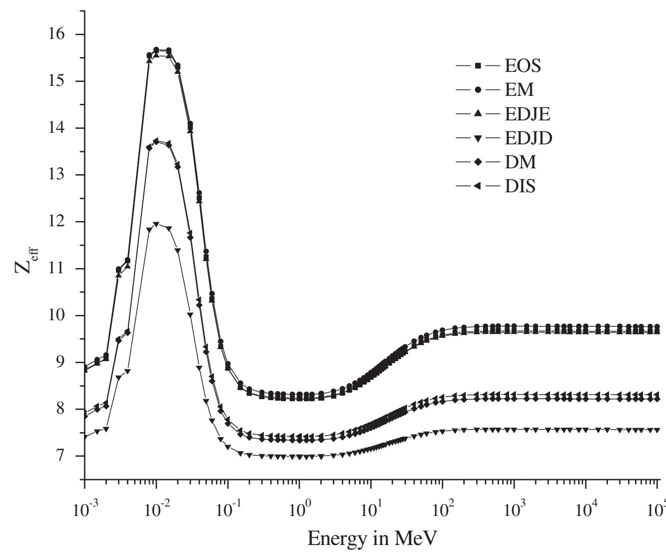

Fig. 2. Variation of effective atomic number with photon energy for teeth.

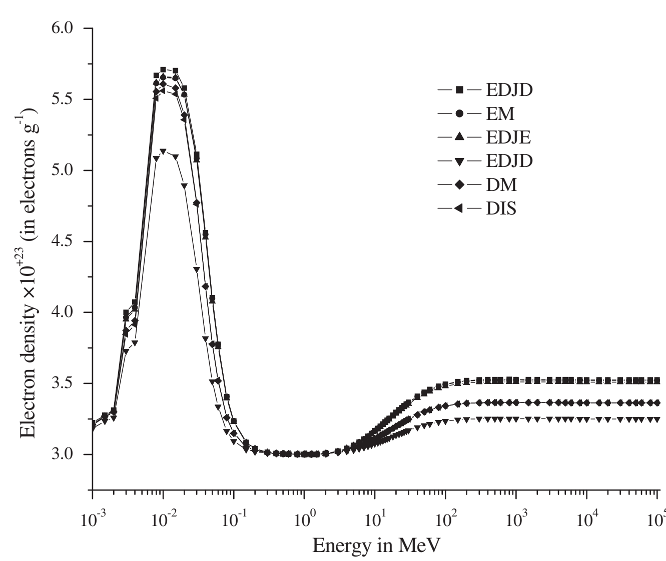

Fig. 3. Variation of effective electron density with photon energy for teeth.

The computed mass attenuation coefficients, effective atomic number and effective electron density for teeth [enamel outer surface (EOS), enamel middle (EM), enamel dentin junction towards enamel (EDJE), enamel dentin junction towards dentin (EDJD), dentin middle (DM) and dentin inner surface (DIS)] for a wide energy range (1 keV–100 GeV) are as shown in Figs. 1–3, respectively. The computed mass attenuation coefficients, effective atomic number and effective electron density help in the basic understanding of photon interaction in teeth. The mass attenuation coefficient measures the number of photons interacting with the target medium and attenuation depends on effective atomic number and effective electron density.

2.2. Computation of G-P fitting parameters

We have evaluated the G-P fitting parameters for the exposure build-up factors (b, c, a, X_k and d) of different regions of teeth

Table 2
Exposure G-P fitting parameters for EOS.

Energy (MeV)	b	c	a	X_k	d
0.015	1.1465	0.4286	0.1912	14.3096	−0.0977
0.02	1.3399	0.4981	0.1652	14.5779	−0.0845
0.03	2.0100	0.7023	0.0919	16.2531	−0.0487
0.04	3.0455	0.9679	0.0179	13.6495	−0.0157
0.05	3.9483	1.2662	−0.0462	13.5929	0.0133
0.06	4.4862	1.5165	−0.0904	13.7165	0.0360
0.08	4.6773	1.8368	−0.1376	13.7186	0.0595
0.1	4.4125	1.9944	−0.1567	13.8860	0.0675
0.15	3.8270	2.0330	−0.1581	14.4967	0.0610
0.2	3.2943	2.0562	−0.1642	14.0738	0.0649
0.3	2.8545	1.9250	−0.1505	14.1941	0.0572
0.4	2.6182	1.8104	−0.1381	14.2559	0.0527
0.5	2.4658	1.7102	−0.1258	14.2483	0.0475
0.6	2.3540	1.6250	−0.1141	14.4006	0.0426
0.8	2.1800	1.5239	−0.1013	14.3089	0.0414
1	2.0925	1.4135	−0.0830	14.4489	0.0326
1.5	1.9253	1.2627	−0.0564	14.5057	0.0230
2	1.8339	1.1633	−0.0359	15.3290	0.0136
3	1.7090	1.0523	−0.0110	12.7039	0.0019
4	1.6227	0.9901	0.0041	19.9341	−0.0071
5	1.5518	0.9477	0.0160	14.4767	−0.0118
6	1.5042	0.9168	0.0254	15.3313	−0.0230
8	1.4162	0.8918	0.0330	12.3887	−0.0199
10	1.3572	0.8723	0.0393	13.9326	−0.0258
15	1.2649	0.8406	0.0510	14.9816	−0.0399

Table 3
Exposure G-P fitting parameters for EM.

Energy (MeV)	b	c	a	X_k	d
0.015	1.1435	0.4270	0.1922	14.2278	−0.0982
0.02	1.3331	0.4949	0.1667	14.5457	−0.0855
0.03	1.9911	0.6955	0.0945	16.2028	−0.0500
0.04	3.0083	0.9589	0.0202	13.7306	−0.0167
0.05	3.9044	1.2513	−0.0424	13.6132	0.0114
0.06	4.4410	1.4999	−0.0869	13.7043	0.0340
0.08	4.6414	1.8198	−0.1347	13.7147	0.0579
0.1	4.3865	1.9785	−0.1543	13.8978	0.0660
0.15	3.8113	2.0217	−0.1565	14.5020	0.0601
0.2	3.2863	2.0457	−0.1627	14.0874	0.0640
0.3	2.8497	1.9178	−0.1494	14.1923	0.0565
0.4	2.6148	1.8049	−0.1372	14.2762	0.0521
0.5	2.4630	1.7062	−0.1251	14.2632	0.0471
0.6	2.3516	1.6219	−0.1135	14.4254	0.0422
0.8	2.1785	1.5214	−0.1008	14.3301	0.0410
1	2.0908	1.4121	−0.0827	14.4793	0.0324
1.5	1.9242	1.2620	−0.0562	14.5228	0.0229
2	1.8330	1.1630	−0.0358	15.3071	0.0136
3	1.7084	1.0524	−0.0110	12.6495	0.0019
4	1.6223	0.9902	0.0042	19.7611	−0.0072
5	1.5514	0.9479	0.0160	14.4944	−0.0120
6	1.5040	0.9167	0.0256	15.2341	−0.0231
8	1.4160	0.8920	0.0330	12.4169	−0.0200
10	1.3570	0.8724	0.0394	13.9142	−0.0260
15	1.2648	0.8402	0.0513	14.9658	−0.0404

Table 4
Exposure G-P fitting parameters for EDJE.

Energy (MeV)	b	c	a	X_k	d
0.015	1.1459	0.4283	0.1914	14.2931	−0.0978
0.02	1.3385	0.4974	0.1655	14.5714	−0.0847
0.03	2.0061	0.7009	0.0925	16.2427	−0.0489
0.04	3.0376	0.9660	0.0184	13.6667	−0.0159
0.05	3.9387	1.2629	−0.0454	13.5973	0.0129
0.06	4.4761	1.5128	−0.0896	13.7138	0.0355
0.08	4.6690	1.8329	−0.1369	13.7177	0.0592
0.1	4.4063	1.9906	−0.1561	13.8888	0.0671
0.15	3.8232	2.0303	−0.1577	14.4980	0.0607
0.2	3.2924	2.0536	−0.1638	14.0771	0.0647
0.3	2.8533	1.9232	−0.1502	14.1937	0.0570
0.4	2.6174	1.8090	−0.1379	14.2608	0.0525
0.5	2.4652	1.7092	−0.1256	14.2520	0.0474
0.6	2.3534	1.6242	−0.1140	14.4066	0.0425
0.8	2.1796	1.5233	−0.1012	14.3140	0.0413
1	2.0921	1.4131	−0.0829	14.4563	0.0325
1.5	1.9251	1.2626	−0.0564	14.5098	0.0230
2	1.8337	1.1632	−0.0358	15.3237	0.0136
3	1.7089	1.0523	−0.0110	12.6907	0.0019
4	1.6226	0.9902	0.0042	19.8921	−0.0071
5	1.5517	0.9477	0.0160	14.4810	−0.0118
6	1.5041	0.9168	0.0255	15.3078	−0.0230
8	1.4161	0.8919	0.0330	12.3955	−0.0199
10	1.3571	0.8723	0.0393	13.9282	−0.0258
15	1.2648	0.8405	0.0511	14.9779	−0.0400

Table 5
Exposure G-P fitting parameters for EDJD.

Energy (MeV)	b	c	A	X_k	d
0.015	1.2400	0.4775	0.1700	14.2716	−0.0852
0.02	1.5553	0.5917	0.1281	15.0580	−0.0623
0.03	2.6475	0.8513	0.0506	15.6239	−0.0384
0.04	3.9748	1.2896	−0.0547	13.5875	0.0200
0.05	5.0680	1.6481	−0.1140	13.8585	0.0493
0.06	5.5335	1.9432	−0.1546	13.6918	0.0716
0.08	5.4455	2.2871	−0.1943	13.3115	0.0893
0.1	5.2138	2.3153	−0.1914	14.3901	0.0827
0.15	3.9729	2.4559	−0.2093	14.1102	0.0944
0.2	3.3973	2.4099	−0.2082	13.3316	0.0892
0.3	2.9632	2.1437	−0.1802	14.0622	0.0756
0.4	2.7009	1.9774	−0.1632	14.0464	0.0691
0.5	2.5387	1.8361	−0.1462	14.1304	0.0613
0.6	2.4069	1.7377	−0.1341	14.1068	0.0572
0.8	2.2414	1.5807	−0.1121	14.0286	0.0485
1	2.1234	1.4744	−0.0961	13.9688	0.0427
1.5	1.9683	1.2703	−0.0581	14.8030	0.0247
2	1.8583	1.1761	−0.0400	13.9484	0.0175
3	1.7182	1.0610	−0.0140	13.9372	0.0047
4	1.6311	0.9890	0.0040	15.7180	−0.0044
5	1.5621	0.9400	0.0180	13.5865	−0.0128
6	1.5171	0.9011	0.0300	12.4741	−0.0186
8	1.4231	0.8868	0.0330	11.7134	−0.0161
10	1.3611	0.8728	0.0370	14.1941	−0.0221
15	1.2710	0.8410	0.0480	15.0422	−0.0339

using the following expression, which is based on Lagrange's interpolation technique:

$$P_{Z_{eff}} = \sum \left(\frac{\prod_{Z' \neq Z}(Z_{eff} - Z)}{\prod_{z \neq Z}(z - Z)} \right) P_z \quad (6)$$

where lower case z is the atomic number of the element of known G-P fitting parameter P_z adjacent to the effective atomic number (Z_{eff}) of the given material whose G-P fitting parameter $P_{Z_{eff}}$ is desired and upper case Z are atomic numbers of other elements of known G-P fitting parameters adjacent to Z_{eff}. The value of G-P fitting parameters (b, c, a, X_k and d) for the element adjacent to Z_{eff} is provided by the standard data available in the literature (ANSI/ANS 6.4.3). The evaluated G-P fitting parameters for the exposure build-up factors of teeth [enamel outer surface (EOS), enamel middle (EM), enamel dentin junction towards enamel (EDJE), enamel dentin junction towards dentin (EDJD), dentin middle (DM) and dentin inner surface (DIS)] are given in Tables 2–7.

Table 6
Exposure G-P fitting parameters for DM.

Energy (MeV)	b	c	a	X_k	d
0.015	1.2030	0.4586	0.1779	14.3541	−0.0899
0.02	1.4708	0.5549	0.1423	14.8655	−0.0706
0.03	2.4001	0.7937	0.0659	15.9671	−0.0421
0.04	3.6255	1.1647	−0.0273	13.5286	0.0063
0.05	4.6483	1.5059	−0.0902	13.7259	0.0367
0.06	5.1464	1.7855	−0.1322	13.7083	0.0592
0.08	5.1671	2.1213	−0.1744	13.4755	0.0790
0.1	4.9143	2.2011	−0.1799	14.1685	0.0781
0.15	3.9317	2.2948	−0.1900	14.2625	0.0817
0.2	3.3641	2.2768	−0.1919	13.6129	0.0803
0.3	2.9240	2.0619	−0.1693	14.1178	0.0689
0.4	2.6707	1.9149	−0.1539	14.1078	0.0631
0.5	2.5120	1.7887	−0.1386	14.1589	0.0561
0.6	2.3878	1.6949	−0.1266	14.1967	0.0517
0.8	2.2179	1.5602	−0.1083	14.1168	0.0460
1	2.1127	1.4509	−0.0910	14.1270	0.0388
1.5	1.9519	1.2679	−0.0576	14.6613	0.0241
2	1.8493	1.1710	−0.0383	14.5489	0.0159
3	1.7151	1.0573	−0.0128	13.5084	0.0036
4	1.6281	0.9894	0.0040	17.6455	−0.0055
5	1.5583	0.9429	0.0172	13.9260	−0.0121
6	1.5121	0.9076	0.0279	13.7685	−0.0204
8	1.4205	0.8886	0.0330	11.9287	−0.0173
10	1.3598	0.8726	0.0378	14.1198	−0.0234
15	1.2685	0.8414	0.0488	15.0359	−0.0359

Table 7
Exposure G-P fitting parameters for DIS.

Energy (MeV)	b	c	a	X_k	d
0.015	1.2220	0.4686	0.1737	14.3025	−0.0874
0.02	1.5149	0.5739	0.1348	14.9477	−0.0661
0.03	2.5341	0.8230	0.0581	15.8112	−0.0407
0.04	3.8174	1.2334	−0.0427	13.5595	0.0140
0.05	4.8811	1.5858	−0.1038	13.7998	0.0440
0.06	5.3617	1.8752	−0.1451	13.6915	0.0664
0.08	5.3229	2.2164	−0.1859	13.3723	0.0850
0.1	5.0864	2.2655	−0.1864	14.2983	0.0807
0.15	3.9541	2.3872	−0.2011	14.1734	0.0891
0.2	3.3821	2.3534	−0.2013	13.4419	0.0854
0.3	2.9462	2.1086	−0.1755	14.0841	0.0727
0.4	2.6878	1.9505	−0.1592	14.0741	0.0665
0.5	2.5272	1.8157	−0.1429	14.1421	0.0591
0.6	2.3984	1.7194	−0.1309	14.1462	0.0549
0.8	2.2314	1.5717	−0.1105	14.0662	0.0474
1	2.1187	1.4644	−0.0939	14.0354	0.0410
1.5	1.9613	1.2691	−0.0578	14.7480	0.0244
2	1.8544	1.1739	−0.0393	14.1996	0.0168
3	1.7168	1.0595	−0.0135	13.7661	0.0042
4	1.6298	0.9892	0.0040	16.4802	−0.0048
5	1.5605	0.9412	0.0177	13.7238	−0.0125
6	1.5149	0.9037	0.0291	13.0033	−0.0193
8	1.4220	0.8877	0.0330	11.7772	−0.0165
10	1.3605	0.8728	0.0373	14.1727	−0.0226
15	1.2700	0.8412	0.0483	15.0383	−0.0347

2.3. Computation of exposure build-up factors

The computed G-P fitting parameters (b, c, a, X_k and d) are used to compute the exposure build-up factors of teeth in the energy range 0.015–15 MeV up to a penetration depth of 40 mean free path with the help of the G-P fitting formula, as given by the equations

$$B(E,X) = 1 + \frac{b-1}{K-1}(K^X - 1) \text{ for } K \neq 1$$

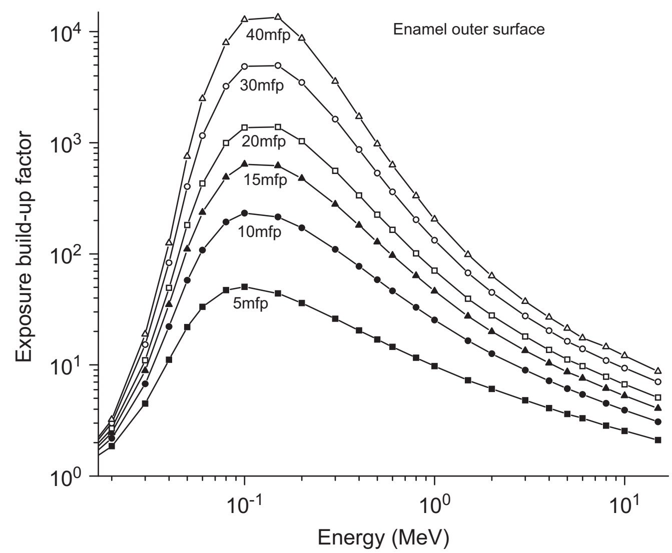

Fig. 4. Variation of exposure build-up factor with photon energy for enamel outer surface (EOS).

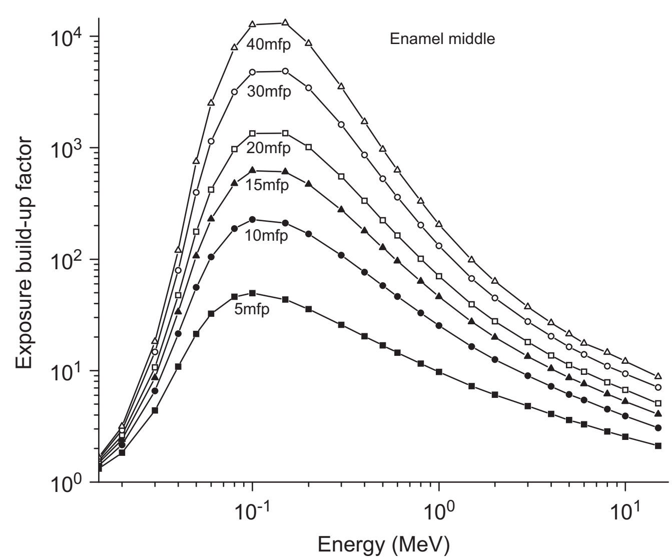

Fig. 5. Variation of exposure build-up factor with photon energy for enamel middle (EM).

$B(E,X)=1+(b-1)X$ for $K=1$

$$K(E,X)=CX^a+d\frac{\tanh((X/X_K)-2)-\tanh(-2)}{1-\tanh(-2)}$$
for penetration depth$(X)\leq 40$ mfp

where X is the source–detector distance for the medium in mean free paths (mfp) and b the value of the exposure build-up factor at 1 mfp. $K(E,X)$ is the dose multiplication factor, and b, c, a, X_k and d are computed G-P fitting parameters that depend on the attenuating medium and source energy.

3. Results and discussion

3.1. Variation of exposure build-up factors with incident photon energy

The variation of exposure build-up factors with incident photon energy for teeth [enamel outer surface (EOS), enamel middle (EM), enamel dentin junction towards enamel (EDJE), enamel dentin junction towards dentin (EDJD), dentin middle (DM) and dentin inner surface (DIS)] is as shown in Figs. 4–9, respectively. From these figures it is observed that the exposure build-up factors increase up to E_{pe} and then decrease. Here E_{pe} is the energy value at which photoelectric interaction coefficients match with Compton interaction coefficients for a given value of effective atomic number (Z_{eff}). For all the given materials E_{pe} is almost equal to 0.1 MeV. The variation of exposure build-up factors with energy is due to the dominance of photoelectric absorption in the lower end and dominance of pair production in the higher photon energy region. In the lower energy end photoelectric absorption is dominant; hence, the exposure build-up factor values are minimum. As the energy of the incident photon increases, Compton scattering overtakes photoelectric absorption. It results in multiple Compton scattering events, which increase the exposure build-up factor to maximum at E_{pe}. Thereafter (above 1 MeV), pair production starts dominating (absorption process), which reduces the exposure build-up factor to a minimum value.

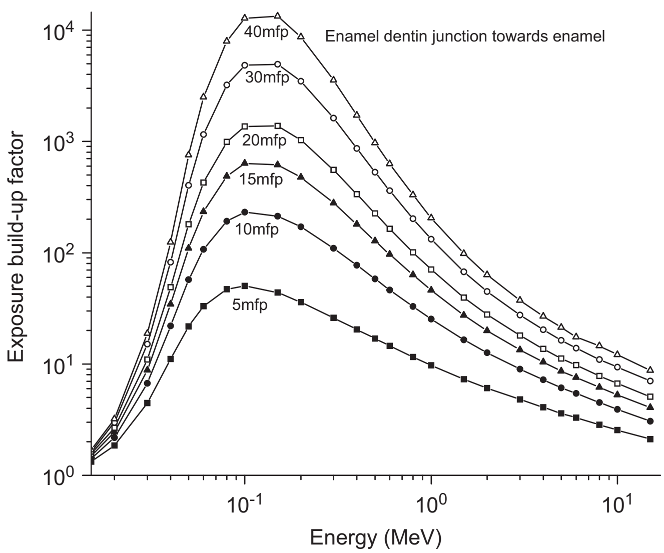

Fig. 6. Variation of exposure build-up factor with photon energy for enamel dentin junction towards enamel (EDJE).

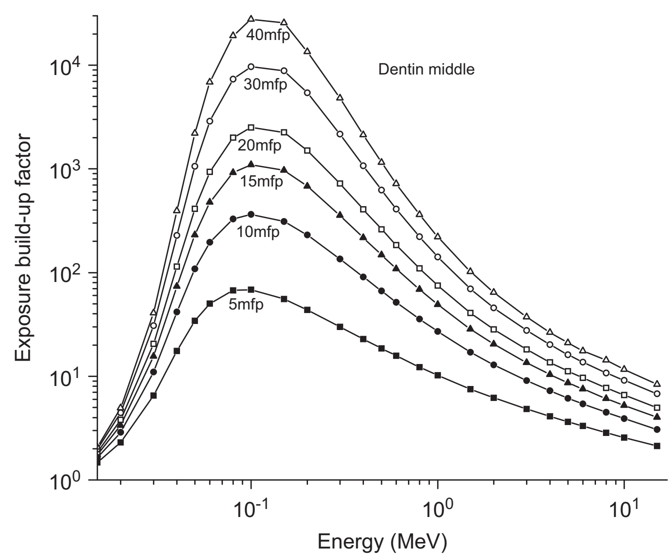

Fig. 8. Variation of exposure build-up factor with photon energy for enamel dentin middle (DM).

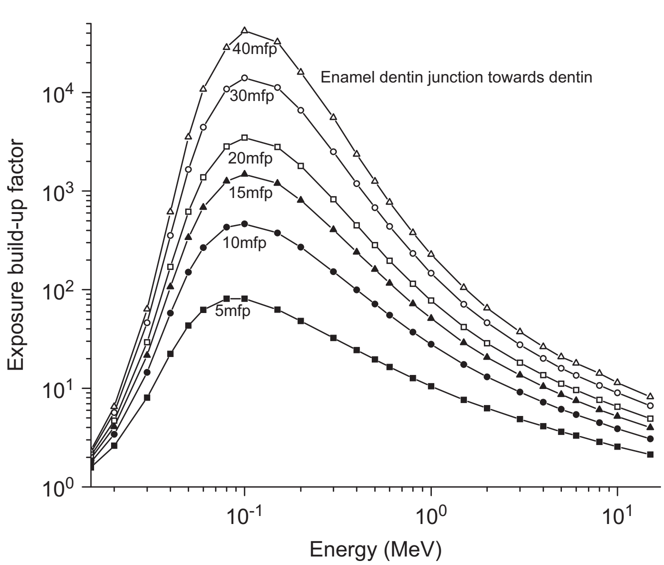

Fig. 7. Variation of exposure build-up factor with photon energy for enamel dentin junction towards enamel (EDJD).

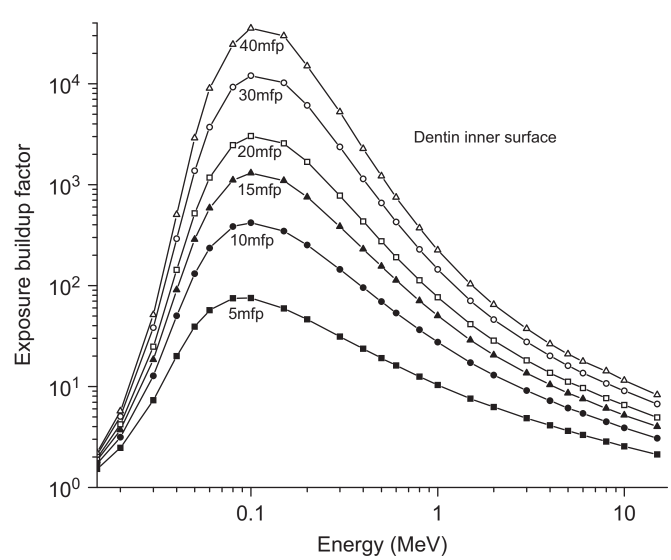

Fig. 9. Variation of exposure build-up factor with photon energy for dentin inner surface (DIS).

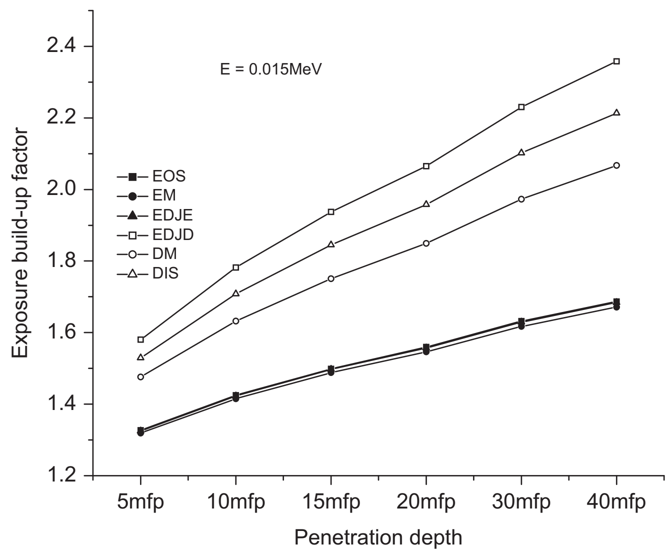

Fig. 10. Variation of exposure build-up factor with penetration depth of teeth at 0.015 MeV.

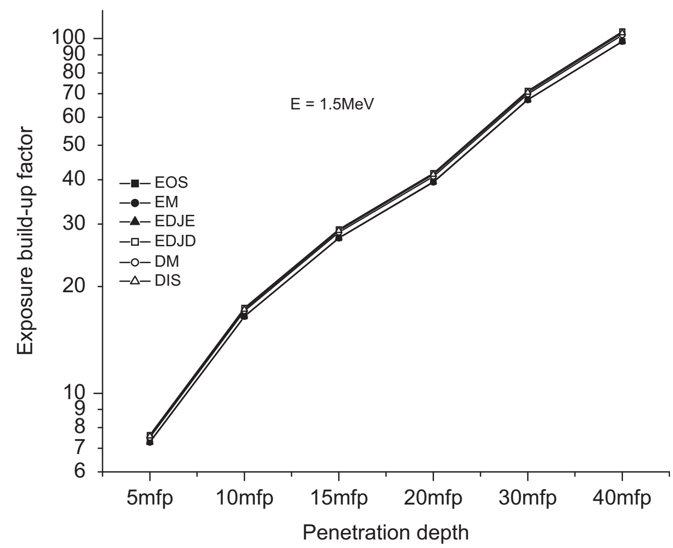

Fig. 12. Variation of exposure build-up factor with penetration depth of teeth at 1.5 MeV.

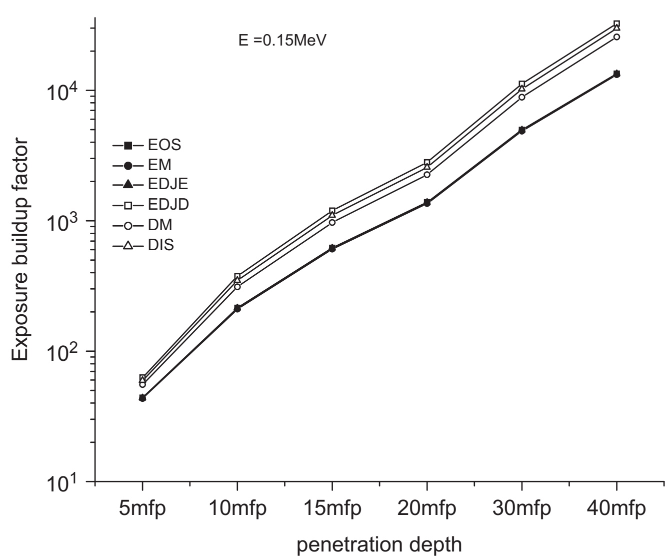

Fig. 11. Variation of exposure build-up factor with penetration depth of teeth at 0.15 MeV.

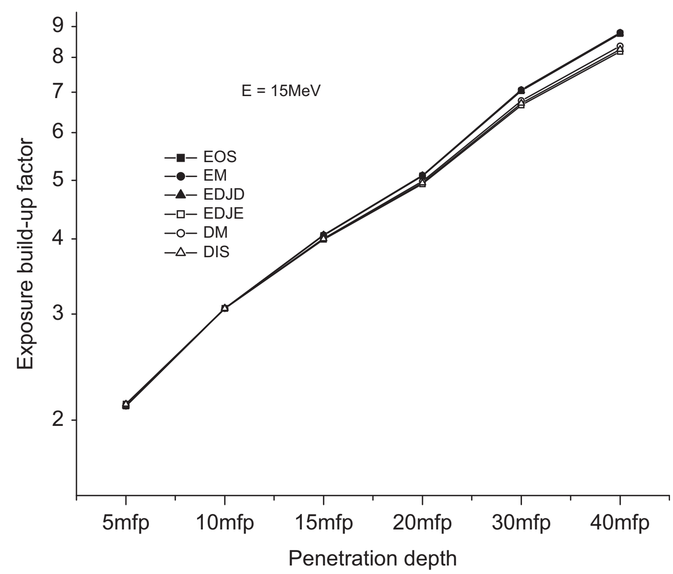

Fig. 13. Variation of exposure build-up factor with penetration depth of teeth at 15 MeV.

3.2. Dependence of exposure build-up factors on penetration depth

The variations of exposure build-up factors with penetration depth of teeth at 0.015, 0.15, 1.5 and 15 MeV are shown in Figs. 10–13, respectively. The exposure build-up factor increases with penetration depth of teeth. With increase in penetration depth, thickness of the interacting material increases, which results in increase of scattering events in the teeth. Hence it results in large exposure build-up factor values. So the degree of violation of the Lambert–Beer ($I=I_0e^{-\mu t}$) law is less for small penetration depth.

3.3. Dependence of exposure build-up factors on Z_{eff}

Figs. 14 and 15 show variation of exposure build-up factor with Z_{eff} at 10 and 40 mfp, respectively, for some randomly selected values of incident photon energies. In the lower energy region (0.015–0.1 MeV), the exposure build-up factor shows a decreasing trend. In the energy region 0.1–0.8 MeV, the decreasing trend of exposure build-up factor is less pronounced. In the lower energy region, photoelectric absorption is the most dominant process. So for a particular value of incident photon energy, as one moves from lower to higher Z_{eff} side, the photons are readily absorbed by photoelectric interaction, so their life time in the material is small, which results in decrease in the value of the exposure build-up factor. This confirms the fact that the chemical composition of different regions of teeth does not affect their attenuation properties at these energies (1, 10, 15 MeV).

3.4. Dependence of exposure build-up factors on N_{el}

The variations of exposure build-up factor with N_{el} for different photon energies at 10 and 40 mfp are shown in Figs. 16 and 17, respectively. The exposure build-up factors show a slight increasing trend with effective electron density. With increase

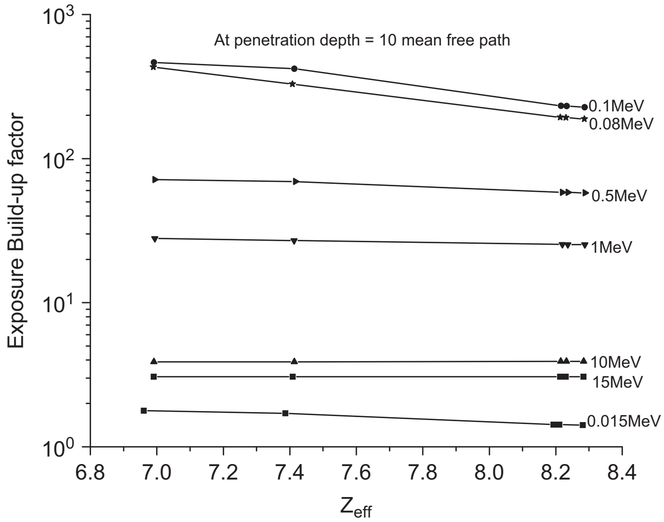

Fig. 14. Variation of exposure build-up factor with effective atomic number for different photon energies at 10 mfp.

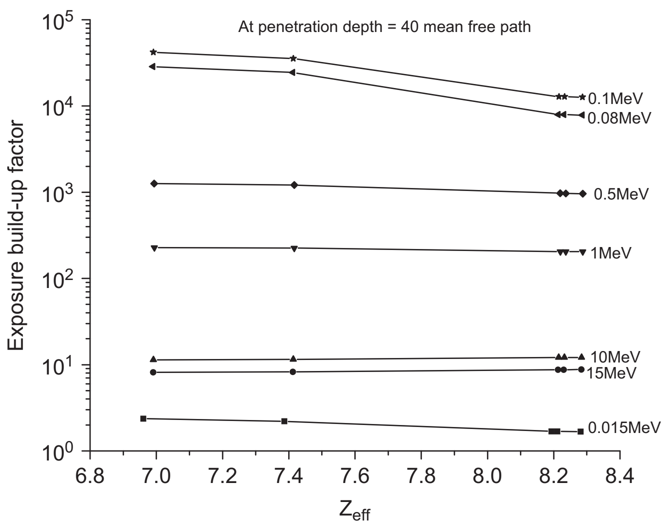

Fig. 15. Variation of exposure build-up factor with effective atomic number for different photon energies at 40 mfp.

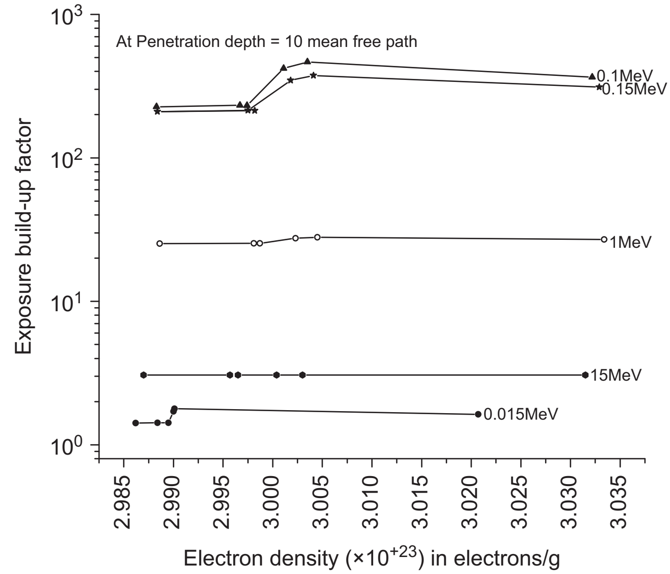

Fig. 16. Variation of exposure build-up factor with effective electron density for different photon energies at 10 mfp.

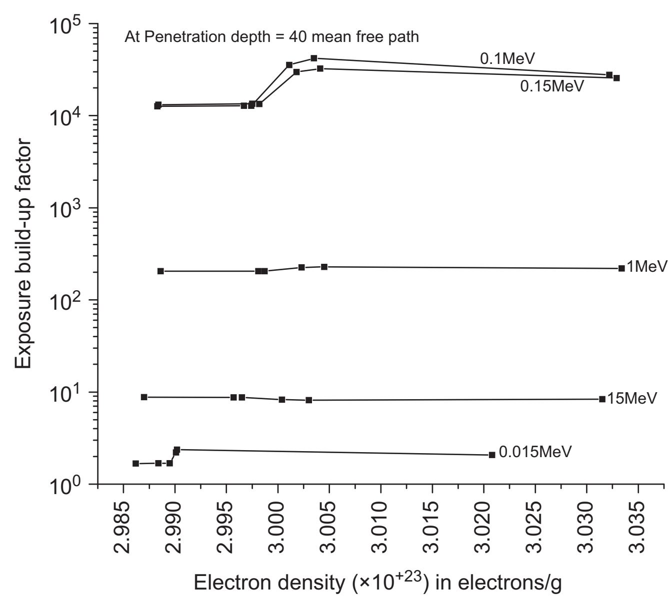

Fig. 17. Variation of exposure build-up factor with effective electron density for different photon energies at 40 mfp.

in N_{el}, electrons available for interaction also increase, which results in increase in scattering events in the teeth. Hence it results in large exposure build-up factor values. So the degree of violation of the Lambert–Beer ($I=I_0e^{-\mu t}$) law is less for low N_{el}.

4. Application of the present work

The radial dependence of dose is $\exp(-\mu r)B/r^2$, where μ denotes the linear attenuation coefficient for the appropriate photon energy and B is the exposure build-up factor. Dose distribution at a distance r is given by

$$D_r = D_0 e^{-\mu r}\frac{B}{r^2} \tag{7}$$

Here D_0 is the initial dose delivered by the point gamma ray emitter. The relative dose distribution at a distance r is

$$\frac{D_r}{D_0} = e^{-\mu r}\frac{B}{r^2} \tag{8}$$

Hence the relative dose distribution can be evaluated using estimated exposure build-up for different penetration depths. The calculation of dose distribution around point gamma ray emitters in different portions of teeth is useful in clinical dosimetry.

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