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ARTICLE

Study of Effective Atomic Number, Mass Energy Absorption Coefficient and Absorbed Dose Rate in Human Organ and Tissue Substitutes

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Abstract: The effective atomic number and mass energy absorption coefficient are two essential parameters used to investigate the radiation response of composite materials of dosimetric interest in many medical applications. The effective atomic number of nine selected human tissues and eleven samples of tissue substitute materials were computed using two methods, the interpolation method and the direct method in the energy range used in brachytherapy applications (0.1-2.0) MeV. The applicability of using the effective atomic number values to investigate scatter and absorption properties of some tissue substitutes, against that of the corresponding human tissues, to validate their tissue-equivalency, is examined. The effect of partial interaction cross sections is also explicitly discussed. Further, the absorbed dose rate, for an isotropic point source, in the selected tissue samples was computed using their estimated mass energy absorption coefficient values. The obtained data are analyzed and differences in sample dose rate relative to water, for photon energies of interest, are evaluated. The results indicate that numbers of tissue substitute samples yield estimates of dose rate to within 5% of dose rate of their corresponding human tissues. The obtained results are expected to be useful in improving dose calculation accuracy in brachytherapy treatment planning or dose evaluation after treatment.

Keywords: Dosimetry, Human organs and tissues, Tissue equivalent materials, Equivalent atomic number, Attenuation and absorption coefficients.

1. Introduction

Among the currents cancer treatment modalities, the most common are chemotherapy, radiotherapy, and surgery [1]. In brachytherapy, radioactive seeds are planted in patient's body to destroy cancer tumor [2]. Although not actual point sources, these photon-emitting seeds are generally very small as compared to the tumor volumes being treated. Development of near-field dosimetry of these sources, however, poses a serious challenge for accurate dose description for the volume of interest and problems involved with dose measurements are still far from being totally resolved and more work is needed.

A successful brachytherapy treatment planning process requires minimizing the discrepancies between calculated dose distributions and delivered doses [3, 4]. Nowadays, several methods have been implemented to assess the absorbed dose near sources by making use of standard data sets and

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phantoms. The absorbed dose to water is the relevant quantity for dose specification, but the conversion of such measurements to tissue adds an undesirable degree of uncertainty stemming from the variations in molecular composition and uniformity of the water. The phantoms, designed to be part of quality assurance protocol, are made from tissue equivalent materials to simulate human tissues to be irradiated. However, currently available tissue equivalent materials show limitations in simulating the human tissues in low and high energy ranges [5]. In a number of previous studies, the dose-rate distribution in different tissue-equivalent materials was determined. Yazdani and Mowlavi [6] have calculated relative dose distributions in water and soft tissue phantoms and dosimetric parameters of a ^{131}Cs brachytherapy source, using a Monte Carlo study. Over the last decade, there was a growing interest in theoretical and computational works for extracting material characteristics using multi-parameter approximations based on theoretical photon-tissue interaction models [7-12]. The results have shown that radial dose functions were influenced in bone tissue and concluded that clinical parameters do not provide enough dose calculation accuracy for different materials.

Effective atomic number (Z_{eff}) is a convenient parameter used to investigate the radiation response of composite materials in many medical applications. It is an essential parameter to study tissue equivalence, photon absorption and photon scattering of composite materials. Z_{eff} has no constant value for a given material, but varies with photon energy and can be evaluated by different methods such as direct method [13] and interpolation method [14], using various parameters, like atomic cross section and attenuation coefficients.

On the other hand mass–energy absorption coefficient (μ_{en}/ρ) is an essential parameter in determining and estimating radiation dose absorbed by the biological molecules when irradiated by photons [15-18]. It is the most useful form for determining radiation exposure or dose when a flux of x-rays or gamma rays is known or can be determined [19-21]. However, it is worth noting that the mass energy absorption coefficients (μ_{en}/ρ) cannot be measured directly, but are instead derived from the mass attenuation coefficients (μ/ρ) in terms of the theoretical factors provided by [22]. Tabulated values of μ/ρ and μ_{en}/ρ at any standard energy of interest in the grid ranging from 20 MeV down to 1 keV for all elements and 48 additional substances of dosimetric interest, have been also provided by [23].

In this work, a procedure was developed to investigate and compare scatter and absorption properties of nine selected human tissues and eleven samples of tissue substitutes. The interaction of photon with tissues is discussed mainly in terms of tissue attenuation and absorption coefficients, equivalent atomic number and absorbed dose-rate variation within the energy range used in brachytherapy. The aim, therefore, was to drive and compute photon interaction parameters, for a number of selected tissue substitutes, in order to apply the concepts of photon interactions and dosimetry and to propose a useful procedure able to determine materials tissue equivalence. The collected data can be beneficial for future advancement of the technology as brachytherapy is characterized by ongoing updates and re-evaluation both for source calibration and for dosimetry calculations.

2. Material and Methods

The chemical compositions of the tissue substitute samples are presented in Table 1 and those of human tissue are listed in Table 2. The data of both tables have been taken from the literature [9, 24-26].

Photon emitting brachytherapy sources are divided into three categories according to their mean energy E : low (E ≤ 30 keV), intermediate (30 keV < E ≤ 300 keV), and high (E > 300 KeV). The brachytherpy sources used in this work included ^{192}Ir (E = 350 keV), ^{137}Cs (662 keV), and ^{60}Co (E = 1.25 MeV) which are all belong to high energy category with similar dosimetric characteristics, however, the energy range was extended to lower energy values, for full investigation and comparison of absorption and scatter behavior of the selected tissue samples where photoelectric absorption dominates.

TABLE 1. Elemental composition (%) of the selected tissue equivalent material, [9, 24-26].

Equivalent material	$\rho(g/cm^3)$	H	C	N	O	S
Gelatin	1.27	0.6281	0.25552	0.05706	0.62109	0.00352
Bee wax	0.964	0.0187	0.7525	0.0842	0.1427	0.0019
Red articulate	0.911	0.0036	0.8017	0.1123	0.0814	0.0009
Paraffin1	0.959	0.0061	0.8173	0.0074	0.1681	0.0010
Bolus	1.112	0.0050	0.8222	0.0078	0.1641	0.0009
Nylon	1.160	0.0063	0.5949	0.0434	0.3158	0.0396
Orange wax	0.931	0.0273	0.8200	0.0737	0.0782	0.0008
Modelling clay	1.273	0.0000	0.1976	0.0086	0.7583	0.0355
PMMA	1.178	0.0024	0.9496	0.0471	0.000	0.0010
Pitch	1.14	0.0019	0.4218	0.0042	0.5676	0.0046
Paraffin2	0.918	0.0068	0.7961	0.0963	0.0994	0.0014

TABLE 2. Elemental composition (%) of the selected tissues [24, 25].

Element	Adipose ρ = 0.92 g/cm^3	Skin ρ = 1.10 g/cm^3	Muscle ρ = 1.04 g/cm^3	Brain ρ =1.03 g/cm^3	Blood ρ = 1.06 g/cm^3	Lung ρ = 1.05 g/cm^3	Soft tissue ρ = 1.00 g/cm^3	Bone, Compact ρ = 1.85 g/cm^3	Bone, Cortical ρ = 1.85 g/cm^3
H	11.9477	10.0588	10.1997	11.0667	10.1866	10.1278	10.4472	6.3984	4.7234
C	63.7240	22.8250	12.3000	12.5420	10.0020	10.2310	23.2190	27.8000	14.4330
N	0.7970	4.6420	3.5000	1.3280	2.9640	2.8650	2.4880	2.7000	4.1990
O	23.2333	61.9002	72.9003	73.7723	75.9414	75.7072	63.0238	41.0016	44.6096
Na	0.0500	0.0070	00.0800	0.1840	0.1850	0.1840	0.1130	0.0000	0.0000
Mg	0.0020	0.0060	0.0200	0.0150	0.0040	0.0730	0.0130	0.2000	0.2200
Si	0.0000	0.0000	0.0000	0.0000	0.0030	0.0000	0.0000	0.0000	0.0000
P	0.0160	0.0330	0.2000	0.3540	0.0350	0.0800	0.1330	7.0000	10.4970
S	0.0730	0.1590	0.5000	0.1770	0.1850	0.2250	0.1990	0.2000	0.3150
Cl	0.1190	0.2670	0.0000	0.2360	0.2780	0.2660	0.1340	0.0000	0.0000
K	0.0320	0.0850	0.3000	0.3100	0.1630	0.1940	0.1990	0.0000	0.0000
Ca	0.0020	0.0150	0.0000	0.0090	0.0060	0.0090	0.0230	14.7000	20.9930
Fe	0.0020	0.0010	0.0000	0.0050	0.0460	0.0370	0.0050	0.0000	0.0000
Zn	0.0020	0.0010	0.0000	0.0010	0.0010	0.0010	0.0030	0.0000	0.0100

2.1 Computation of Mass Energy Absorption Coefficient (μ_{en}/ρ)

In several applications of medical physics such as brachytherapy, medium μ_{en}/ρ values are a prerequisite for radiation dosimetry. However, it is worth noting that the mass energy absorption coefficients cannot be measured directly, but are instead derived from the mass attenuation coefficients (μ/ρ).

However, Seltzer and Hubbell [23] have provided the tabulated values of mass attenuation coefficients and mass energy absorption coefficients at standard photon energies in the range of 1 keV up to 20 MeV for all elements and 48 additional substances of dosimetric interest. These are by far considered to be the most reliable set of data among those available in literature. However, for our samples as well as energies not listed in this tabulation, the evaluation of (μ_{en}/ρ) values was accomplished by using an interpolation program to extract μ_{en}/ρ of the constituent elements and then μ_{en}/ρ of the selected materials and tissues were calculated by a computer program that utilizing the mixture rule [19, 27].

The values, calculated were found to agree well with the Seltzer and Hubbell [23] values for some typical samples of biological interest at standard energies.

2.2 Computation of Equivalent Atomic Number (Z_{eq}).

The effective or equivalent atomic number (Z_{eq}) of a tissue or a composite material is similar to the atomic number of a single element and describes the properties of the material with respect to radiation interaction processes. It represents a weighted average of electrons per atom in a material of multi-elements and its value can provide an initial estimation of the chemical composition of the material [28, 29].

The value of Z_{eq}, however, is energy dependent and cannot be represented uniquely by a single number across the entire energy range, as in the case of pure element. Its variation with energy depends on the relative dominance of the partial interaction processes and the difference between the atomic numbers of the constituent elements available in the material [30].

In the present study the Z_{eq} of the selected samples were computed for the energies of interest, using two different methods; the direct method and the interpolation method. These methods use different input parameters such as atomic cross-sections, atomic numbers, and attenuation coefficients, for computation of Z_{eq}. Although it was elaborated in several earlier reports [13, 31] that the direct method is valid for the evaluation of equivalent atomic number, for compounds and mixtures in the energy region of interest, the interpolation method was introduced for the sake of comparison only.

A. The direct method:

The equivalent atomic number (Z_{eq}) of the tissue material was first computed using the practical relation introduced by [13] as:

$$Z_{eq} = \frac{\sum_i f_i A_i \left(\frac{\mu}{\rho}\right)_i}{\sum_i f_i \frac{A_i}{Z_i} \left(\frac{\mu}{\rho}\right)_i} \quad (1)$$

where f_i is the molar fraction in the compound/mixture, A_i is the atomic weight of the element i, Z_i is its atomic number and $(\mu/\rho)_i$ is the mass attenuation coefficient that was obtained using the convenient computer program WinXCom.

B. The interpolation method

The computational work for this method has been carried out in three steps, as follows:

Values of the Compton partial mass attenuation coefficient, (μ_{inc}), and the total mass attenuation coefficient, (μ_m), have been obtained for the elements Z = 4–30, and for the human organs and tissues using the WinXCom program. The equivalent atomic number, Zeq, for a given human organ or tissue is then calculated by matching the ratio, (μ_{inc})/(μ_m), of that human organ or tissue at a given energy with the corresponding ratio of a pure elementat the same energy. If this ratio lies between the two ratios for known elements, then the value of Zeq is interpolated using the following formula: [14, 28].

$$Z_{eq} = \frac{Z_1(logR_2 - logR) + Z_2(logR - logR_1)}{logR_2 - logR_1} \quad (2)$$

where R_1 and R_2 are the (μ_{inc}/μ_m) ratios of the two successive elements of atomic numbers Z_1 and Z_2, respectively; and R is the (μ_{inc}/μ_m) ratio for the selected tissues or materials at a particular energy that lies between R_1 and R_2.

2.3 Computation of Absorbed Dose Rate (D)

Many analytical model algorithms were introduced, in brachytherapy, as treatment-planning tools, for computing more accurate dose distributions for clinical multi-source implants in the presence of tissue-composition and density heterogeneities [32].

The calculation formalism used here for absorbed dose rate $D(R)$ at a distance R from a bracytherapy source included the use of the point source approximation [33].

$$D(R) = \frac{CE}{4\pi R^2}\left(\frac{\mu_{en}}{\rho}\right) \quad (3)$$

where C is source activity (Bq), E is photon energy (MeV) and (μ_{en}/ρ) is medium mass energy absorption coefficient (cm^2/g).

Based on the tissue-specific information obtained previously, the dose-rate, in the selected samples, is estimated at various photon energies within the range 0.015-2.0 MeV, at different distances from the source, and this, we believe, is enough for the purpose of material comparison. To draw a better comparison, however, between the human tissues and tissue substitutes, the fractional differences in their dose-rate values were first calculated, for photon energies emitted by ^{137}Cs, ^{60}Co and ^{192}Ir brachytherapy sources, and then their relative dose rates with respect to water, as a reference material, were calculated and compared.

3. Results and Discussion

3.1 Mass Energy Absorption Coefficient (μ_{en}/ρ)

Fig. 1 shows the variation of the mass attenuation coefficient (μ/ρ) and the mass energy absorption coefficient (μ_{en}/ρ) with photon energy, for soft tissues. Similar to the behavior of μ/ρ, the mass energy absorption coefficient decreases sharply with an increase in photon energy but to lower values, at the energy region where Compton scattering is the pre-dominant interaction, as a number of scattered photons may carry energy out of the encountered medium. After that energy region, a little rise in the μ_{en}/ρ values with photon energy can be noted, due to pair production dominance, and values of both coefficients become close together again as shown in the figure.

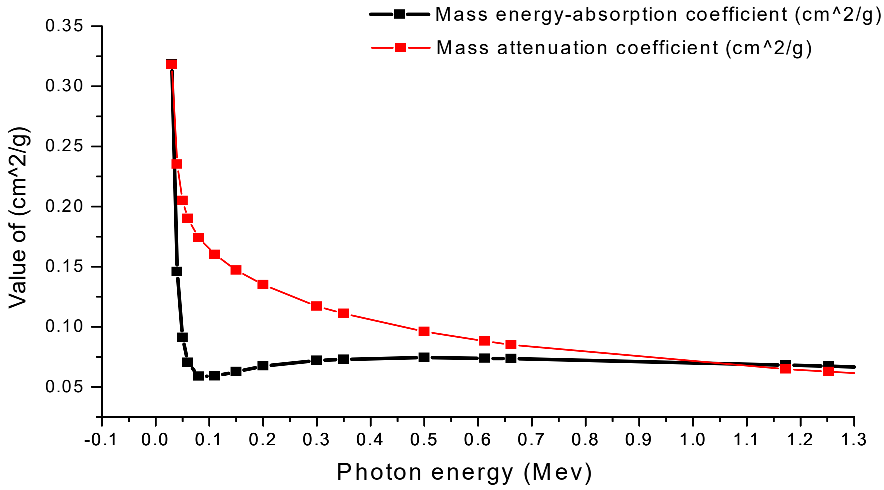

FIG. 1. Variation of (μ_m) and (μ_{en}/ρ) with photon energy for soft tissue.

The major variation in μ_{en}/ρ values is due to the relative dominance of the partial photon interactions. Ignoring a few exceptions, the μ_{en}/ρ values tend to be about constant and similar for all samples, at photon energies above 1.0 MeV that attributes to the dominance of Compton scattering in its energy region. However, at low energy, <100 keV, the photoelectric effect is dominant and so, it is responsible for the variations in the μ_{en}/ρ values according to chemical composition or Z_{eq} of each tissue. Values of mass energy absorption coefficients were computed for all the selected samples and shown graphically in Fig. 2. As can be seen from the figure, comparison of various tissues, using its mass energy absorption coefficient values, is possible. In photoelectric energy region, human tissues and tissue equivalent materials are arranged in bunches, with an envelope of uncertainty ±5%. It is seen that bee wax, paraffin1, paraffin 2, red articulation and bolus are grouped in one bunch while gelatin, brain, muscles and skin tissue are grouped in another bunch. Further, paraffin1 or paraffin 2 present good agreements with human bone tissues in terms of μ_{en}/ρ values but did not show good agreements in terms of mass density. On the other hand, gelatin was found useful to simulate human brain and muscle tissues, in both μ_{en}/ρ and mass density values, which is in good agreement with the results obtained by [9].

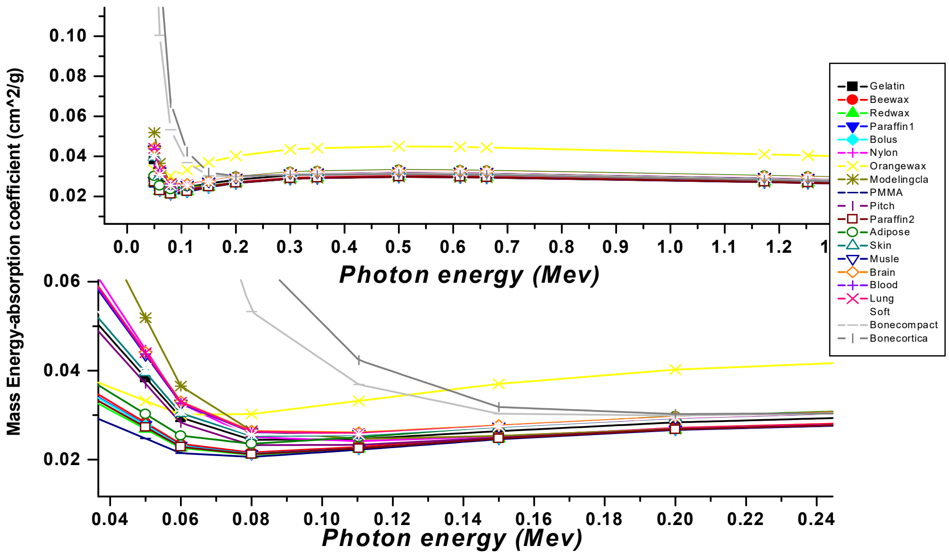

FIG. 2. Comparison of tissues using the energy dependence of its (μ_{en}/ρ) values.

3.2 Equivalent Atomic Number

The equivalent atomic number computed by the direct method and the interpolation method were found in good agreement and almost identical, within 1% difference, in the intermediate photon energy region where Compton interaction dominates. As all the energies of the sources under study are within this intermediate energy range, the energy dependence of mean Z_{eq} values, obtained using both methods, for all the selected samples is plotted in Fig. 3. It is seen from the figure that the equivalent atomic number for composite materials cannot be represented uniquely across the entire energy region by a constant number, as in the case of a single element, but it varies with energy. Its variation could be attributed to material chemical compositions and the partial interaction processes, such as photoelectric effect, Compton scattering and pair production. Consequently, tissues containing elements with high atomic number have comparatively higher Z_{eq} and vice versa. For each material, the upper and lower boundary of Z_{eq} was dictated by the minimum and maximum atomic number in its composition. This explains why compact and cortical bones have the highest Z_{eq} as they both contain about 22% of Ca which has relatively high atomic number and abundance in the two materials [34] in comparison to chemical compositions of the other human tissues and tissue equivalent materials.

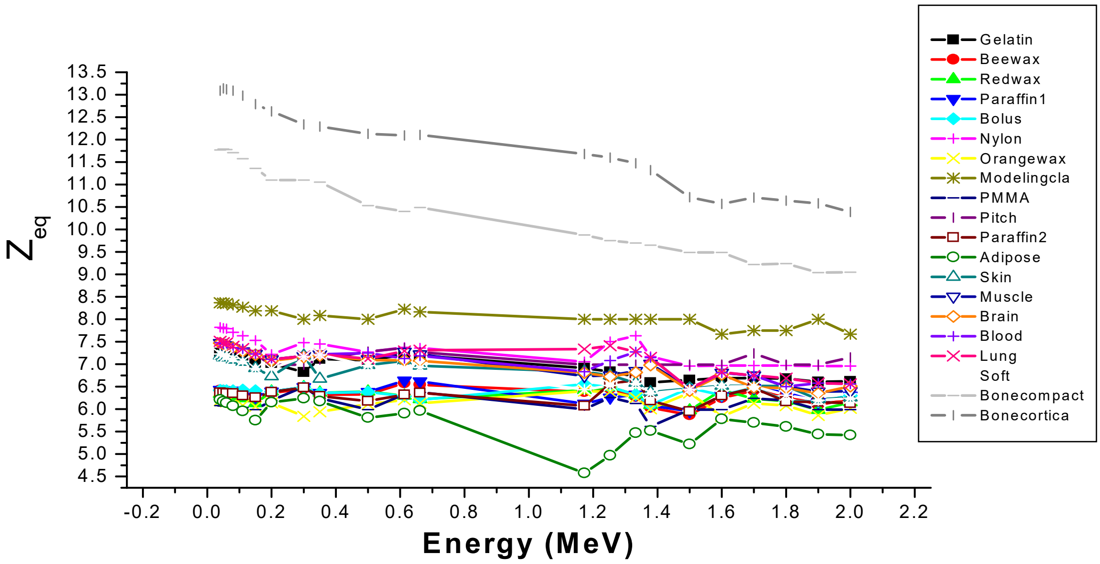

FIG. 3. The energy dependence of Z_{eq} on total interaction, for human tissues and tissue equivalent materials.

Depending on the range of Z_{eq} values, the selected tissues and materials under consideration could be grouped into three categories: low Z_{eq} (5.00 - 6.99), intermediate Z_{eq} (7.00 – 8.99) and high Z_{eq} (9.00 -13.00). In the low energy range from 0.015 to 1.0 MeV the selected tissues and substitute materials are classified as low, intermediate and high equivalent atomic number materials, as shown in Table 3. Above 1 MeV, values of Z_{eq} of a number of materials jump from low to intermediate level. Skin, muscle, brain, soft tissue, gelatin and pitch joined blood, lung and nylon with all of them having Z_{eq} within the range (7 – 8) while adipose tissue, bee wax, red articulate, paraffin 1, bolus, orange articulate wax, PMM and paraffin 2 remained in the low Z_{eq} range with values very close to each other. This means that any of these tissue substitutes, in this group, may be used to simulate adipose tissue since the energy behavior of its Z_{eq} is qualitatively well described by these tissue substitutes for photon energy less than 1MeV.

Fig. 4 shows the variation of the fractional difference in the Z_{eq} values, for human tissues and tissue substitutes, with photon energy. The figure suggests that gelatin can be a good substitute material for brain or muscle tissue in the energy region under consideration with much less than 5% difference. This result is in good agreement with the result reached in the above section. Furthermore, nylon or pitch may simulate skin well in the low energy range from 0.015 to 1.0 MeV and can be useful to simulate lung tissue at a wider energy range up to 1.5 MeV. The figure also shows that gelatin is a good tissue-equivalent material for soft tissue in the wide energy range 0.015 to 2.0 MeV.

TABLE 3. Classification of equivalent atomic number in three groups.

Photon Energy Range	Equivalent Atomic Number Range		
	4 -7	7 – 8	8 – 13
0.015 – 1 MeV	Adipose tissue Skin Muscle Brain Soft tissue Gelatin Bee wax Red articulate Paraffin1 Bolus Orange articulation Wax PMMA Pitch Paraffin2	Blood Lung Nylon	Compact bone Cortical bone Modeling clay
1 – 2 MeV	Adipose tissue Bee wax Red articulate Paraffin1 Bolus Orange articulation Wax PMMA Paraffin2	Blood Lung Nylon Skin Muscle Brain Soft tissue Gelatin Pitch	Compact bone Cortical bone Modeling clay

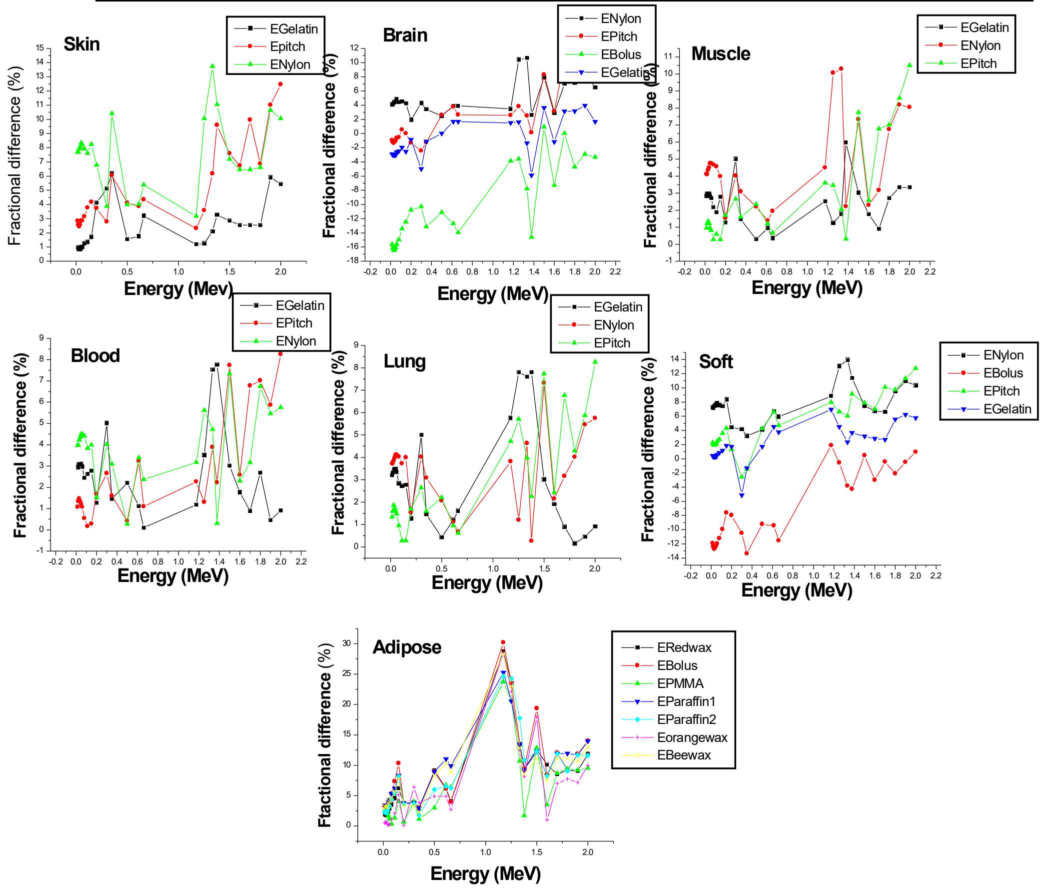

FIG. 4. Variation of the fractional difference in the Z_{eq} values, for human tissues and tissue equivalent materials, with photon energy.

3.3 Absorbed Dose Rate

For photon energies emitted by ^{137}Cs, ^{60}Co and ^{192}Ir brachytherapy sources. Variation of dose-rate with radial distance is computed and presented in Tables 4 and 5 and plotted in Figs. 5 (a-c). Water was added to the calculations as a reference material. It is seen from the listed data that for a given photon energy and radial distance, the dose-rate in each tissue differs from the others due to the differences in their chemical compositions.

At a distance of 2 cm from the ^{137}Cs source for example, the values of dose-rate for adipose tissue and brain tissue are very close to that of water, while it is clearly has lower value for cortical bone and compact bone. This is due to the dominance of Compton scattering in this energy range and bone being of high-Z_{eq} materials (calcium, Z = 20), whereas adipose tissue, brain and water have much lower Z_{eq}. Similar results are observed at photon energies of 1.2529 MeV and 0.350 MeV emitted from ^{60}Co and ^{192}Ir, respectively**.** It is seen in Figs. 5(a)–5(c) that, the difference in the compositions of various tissues has its impact mainly on dose-rate value in points near the source.

TABLE 4. Variation of dose-rate in human tissues and water with radial distance from ^{137}Cs, ^{60}Co and ^{192}Ir sources.

Source	Distance (cm)	Adipose	Skin	Muscle	Brain	Blood	Lung	Soft tissue	Compact Bone	Cortical Bone	Water
		Dose-rate (Gy/h)									
^{137}Cs	2	74.6063	73.4449	73.5609	74.1238	73.5536	73.5132	73.7000	70.9277	69.7951	74.2605
	4	18.6516	18.3612	18.3902	18.5309	18.3884	18.3783	18.4250	17.7319	17.4488	18.5651
	6	8.2896	8.1605	8.1734	8.2360	8.1726	8.1681	8.1889	7.8809	7.7550	8.2512
	8	4.6629	4.5903	4.5976	4.6327	4.5971	4.5946	4.6063	4.4330	4.3622	4.6413
	10	2.9843	2.9378	2.9424	2.9650	2.9421	2.9405	2.9480	2.8371	2.7918	2.9704
	12	2.0724	2.0401	2.0434	2.0590	2.0432	2.0420	2.0472	1.9702	1.9388	2.0628
	14	1.5226	1.4989	1.5012	1.5127	1.5011	1.5003	1.5041	1.4475	1.4244	1.5155
	16	1.1657	1.1476	1.1494	1.1582	1.1493	1.1486	1.1516	1.1082	1.0906	1.1603
	18	0.9211	0.9067	0.9082	0.9151	0.9081	0.9076	0.9099	0.8757	0.8617	0.9168
	20	0.7461	0.7345	0.7356	0.7412	0.7355	0.7351	0.7370	0.7093	0.6980	0.7426
^{60}Co	2	128.6398	126.4823	126.6350	127.5997	126.6108	126.5411	126.9158	121.9347	119.83696	127.7896
	4	32.1600	31.6206	31.6587	31.8999	31.6527	31.6353	31.7289	30.4837	29.9592	31.9474
	6	14.2933	14.0536	14.0706	14.1777	14.0679	14.0601	14.1018	13.5483	13.3152	14.1988
	8	8.0400	7.9052	7.9147	7.9750	7.9132	7.9088	7.9322	7.6209	7.4898	7.9869
	10	5.1456	5.0593	5.0654	5.1040	5.0644	5.0617	5.0766	4.8774	4.7935	5.1116
	12	3.5733	3.5134	3.5176	3.5444	3.5170	3.5150	3.5254	3.3871	3.3288	3.5497
	14	2.6253	2.5813	2.5844	2.6041	2.5839	2.5825	2.5901	2.4885	2.4457	2.6080
	16	2.0100	1.9763	1.9787	1.9937	1.9783	1.9772	1.9831	1.9052	1.8725	1.9967
	18	1.5882	1.5615	1.5634	1.5753	1.5631	1.5622	1.5669	1.5054	1.4795	1.5777
	20	1.2864	1.2648	1.2664	1.2760	1.2661	1.2654	1.2692	1.2194	1.1984	1.2779
^{192}Ir	2	39.1593	38.5084	38.5611	38.8556	38.5526	38.5526	38.6430	37.5543	37.1087	38.8973
	4	9.7898	9.6271	9.6403	9.7139	9.6381	9.6381	9.6607	9.3886	9.2772	9.7243
	6	4.3510	4.2787	4.2846	4.3173	4.2836	4.2836	4.2937	4.1727	4.1232	4.3219
	8	2.4475	2.4068	2.4101	2.4285	2.4095	2.4095	2.4152	2.3472	2.3193	2.4311
	10	1.5664	1.5403	1.5424	1.5542	1.5421	1.5421	1.5457	1.5022	1.4844	1.5560
	12	1.0878	1.0697	1.0711	1.0793	1.0709	1.0709	1.0734	1.0432	1.0308	1.0804
	14	0.7992	0.7859	0.7870	0.7930	0.7868	0.7868	0.7886	0.7664	0.7573	0.7938
	16	0.6119	0.6017	0.6025	0.6071	0.6024	0.6024	0.6038	0.5868	0.5798	0.6077
	18	0.4835	0.4754	0.4761	0.4797	0.4760	0.4759	0.4771	0.4636	0.4581	0.4802
	20	0.3916	0.3851	0.3856	0.3886	0.3855	0.3855	0.3864	0.3755	0.3711	0.3890

TABLE 5. Variation of dose-rate in tissue substitutes with radial distance from the ^{137}Cs, ^{60}Co and ^{192}Ir sources.

Source	Distance (cm)	Gelatin	Bee wax	Red articulate	Paraffin1	Bolus	Nylon	Orange Wax	Modeling Clay	PMMA	Pitch	Paraffin2
		Dose rate (Gy/h)										
^{137}Cs	2	70.960	67.940	66.9235	67.1082	67.0414	67.1617	101.089	66.8467	66.839	66.935	67.1455
	4	17.740	16.9852	16.7309	16.7771	16.7604	16.7904	25.2724	16.7117	16.709	16.733	16.7864
	6	7.8845	7.5490	7.4360	7.4565	7.4491	7.4624	11.2322	7.4274	7.4266	7.4373	7.4606
	8	4.4350	4.2463	4.18272	4.19427	4.1901	4.1976	6.3181	4.1779	4.1775	4.1835	4.1966
	10	2.8384	2.7176	2.6769	2.6843	2.6817	2.6865	4.0436	2.6739	2.6736	2.6774	2.6858
	12	1.9711	1.8872	1.8590	1.8641	1.8623	1.8656	2.8080	1.8569	1.8566	1.8593	1.8652

Source	Distance (cm)	Gelatin	Bee wax	Red articulate	Paraffin1	Bolus	Nylon	Orange Wax	Modeling Clay	PMMA	Pitch	Paraffin2
		Dose rate (Gy/h)										
	14	1.4482	1.3865	1.3658	1.3696	1.3682	1.3707	2.0631	1.3642	1.3641	1.3660	1.3703
	16	1.1088	1.0616	1.0457	1.0486	1.0475	1.0494	1.5795	1.0445	1.0444	1.0459	1.0492
	18	0.8761	0.8388	0.8262	0.8285	0.8277	0.8292	1.2480	0.8253	0.8252	0.8264	0.8290
	20	0.7096	0.6794	0.6692	0.6711	0.6704	0.6716	1.0109	0.6685	0.6684	0.6694	0.6715
	2	122.20	117.1851	115.4566	115.7409	115.6274	115.7419	174.3870	115.0287	115.34	115.28	115.832
	4	30.5505	29.2963	28.8642	28.9352	28.9068	28.9355	43.5967	28.7572	28.8358	28.8208	28.9579
	6	13.578	13.0206	12.8285	12.8601	12.8475	12.8602	19.3763	12.7810	12.8159	12.8092	12.8702
	8	7.6376	7.3241	7.2160	7.2338	7.2267	7.2339	10.8992	7.1893	7.2089	7.2052	7.2395
	10	4.8881	4.6874	4.6183	4.6296	4.6251	4.6297	6.9755	4.6012	4.6137	4.6113	4.6333
^{60}Co	12	3.3945	3.2551	3.2071	3.2150	3.2119	3.2151	4.8441	3.1952	3.2040	3.2023	3.2176
	14	2.4939	2.3915	2.3563	2.3621	2.3597	2.3621	3.5589	2.3475	2.3539	2.3527	2.3639
	16	1.9094	1.8310	1.8040	1.8085	1.8067	1.8085	2.7248	1.7973	1.8022	1.8013	1.8099
	18	1.5087	1.4467	1.4254	1.4289	1.4275	1.4289	2.1529	1.4201	1.4240	1.4233	1.4300
	20	1.2220	1.1719	1.1546	1.1574	1.1563	1.1574	1.7439	1.1503	1.1534	1.1528	1.1583
	2	37.205	35.6791	35.1530	35.2394	35.2048	35.2870	53.0712	35.0654	35.1186	35.1048	35.2675
	4	9.3012	8.9198	8.7882	8.8099	8.8012	8.8218	13.2678	8.7664	8.7797	8.7762	8.8169
	6	4.1339	3.9644	3.9059	3.9155	3.9117	3.9208	5.8968	3.8962	3.9021	3.9005	3.9186
	8	2.3253	2.2299	2.1971	2.2025	2.2003	2.2054	3.3170	2.1916	2.1949	2.1941	2.2042
	10	1.4882	1.4272	1.4061	1.4096	1.4082	1.4115	2.1229	1.4026	1.4047	1.4042	1.4107
^{192}Ir	12	1.0335	0.9911	0.9765	0.9789	0.9779	0.9802	1.4742	0.9740	0.9755	0.9751	0.9797
	14	0.7593	0.7282	0.7174	0.7192	0.7185	0.7201	1.0831	0.7156	0.7167	0.7164	0.7197
	16	0.5813	0.5575	0.5493	0.5506	0.5501	0.5514	0.8292	0.5479	0.5487	0.5485	0.5511
	18	0.4593	0.4405	0.4340	0.4351	0.4346	0.4356	0.6552	0.4329	0.4336	0.4334	0.4354
	20	0.3721	0.3568	0.3515	0.3524	0.3521	0.3529	0.5307	0.3507	0.3512	0.3511	0.3527

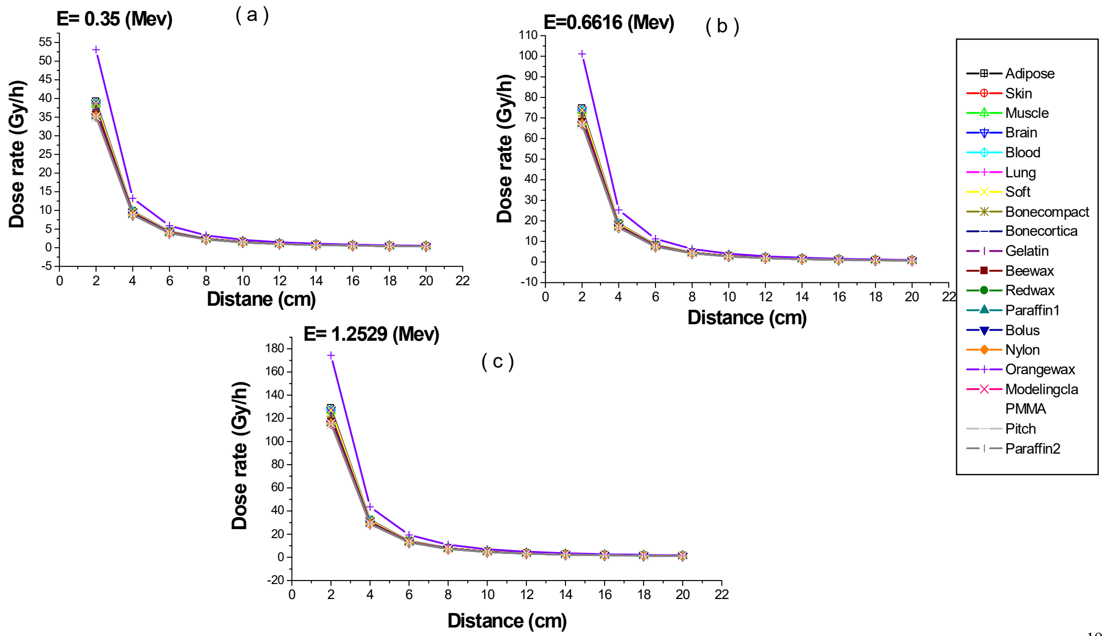

FIG. 5. Variation of dose rate in human tissues and tissue equivalent materials with radial distance for a) ^{192}Ir, b) ^{137}Cs and c) ^{60}Co sources. The results of all samples are plotted and they are too similar to be separable in the plot.

The reason for this effect may be related to the photoelectric absorption of a number of low energy photons in tissue close to the source. This is due to the fact that penetration of high energy photons produces first a large number of secondary photons of low energy, due to multiple scattering, and those photons interact with tissue through photoelectric absorption.

At larger distances, 6-8 cm, from the source, the dose- rate becomes independent of the chemical composition or Z_{eq} due to the removal of low energy photons in the first few centimeters. Furthermore, ignoring a few exceptions, the behavior of human tissues and tissue substitutes was similar at an increased distance from the source so that the phantom size should be taken in consideration when absolute dose calculation is performed.

It should be noted, however, that the data listed in Tables 4 and 5 are related only to a number of selected photon energies in the energy range 0.3<E<1.3 MeV, at which Compton scattering is the main photon interaction process, and the dose-rate is almost independent of the chemical composition. In general, the variation of dose-rate is greater for lower energy photons due to photoelectric interaction. The variation of dose-rate, within a wider range of photon energy 0.015<E<1.5 MeV, was computed and plotted in Fig. 6 and Fig. 7 for both types of the selected samples, at three different distances from the source of 2, 10 and 20 cm. It is evident from the figures, that the maximum sensitivity to tissue composition or the largest relative dose-rate difference occurred at low photon energy of less than 0.2 MeV where photoelectric effect is the dominant absorption process which is one of the factors that causes differences in absorption and scattering properties to occur clearly between different tissues. These results also imply that equating various tissues in dose calculations, in the energy range lower than 0.2 MeV, can introduce a significant error. This can be seen in Table 6 and Table 7 in which the relative dose-rate with respect to dose-rate in water, for all the selected samples, is presented. The relative dose-rate was calculated as the ratio of dose-rate in a given sample to that in water. Its values were computed at a radial distance of 2 cm from the source for different photon energies, in order to show maximum differences between different tissues and materials. Ignoring a few exceptions, the obtained values indicate that the dose-rate in human tissues differs slightly from that in water (2%-5%), while this difference was (5%-10%) for the tissue substitutes in average. Nevertheless, the behavior of dose rate, in all samples and water, with radial distance from the source is similar, with small differences, as shown in Fig. 8.

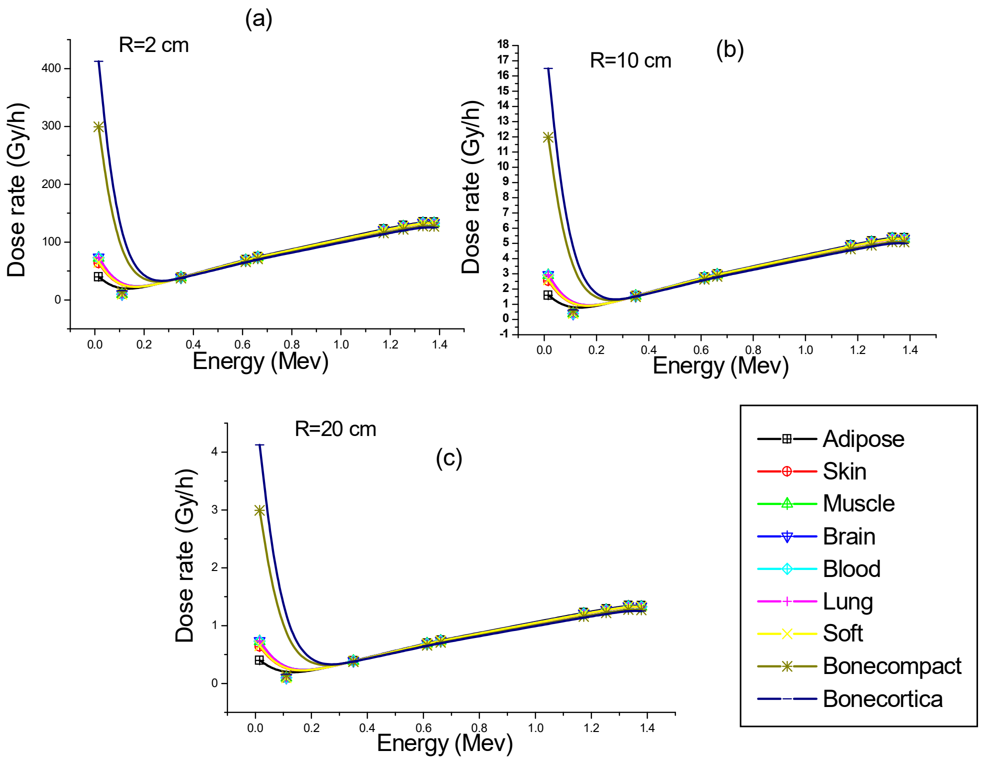

FIG. 6. Variation of dose rate in human tissues with photon energy (0.015<E<1.5 MeV) at three different distances of 2, 10 and 20 cm from the source.

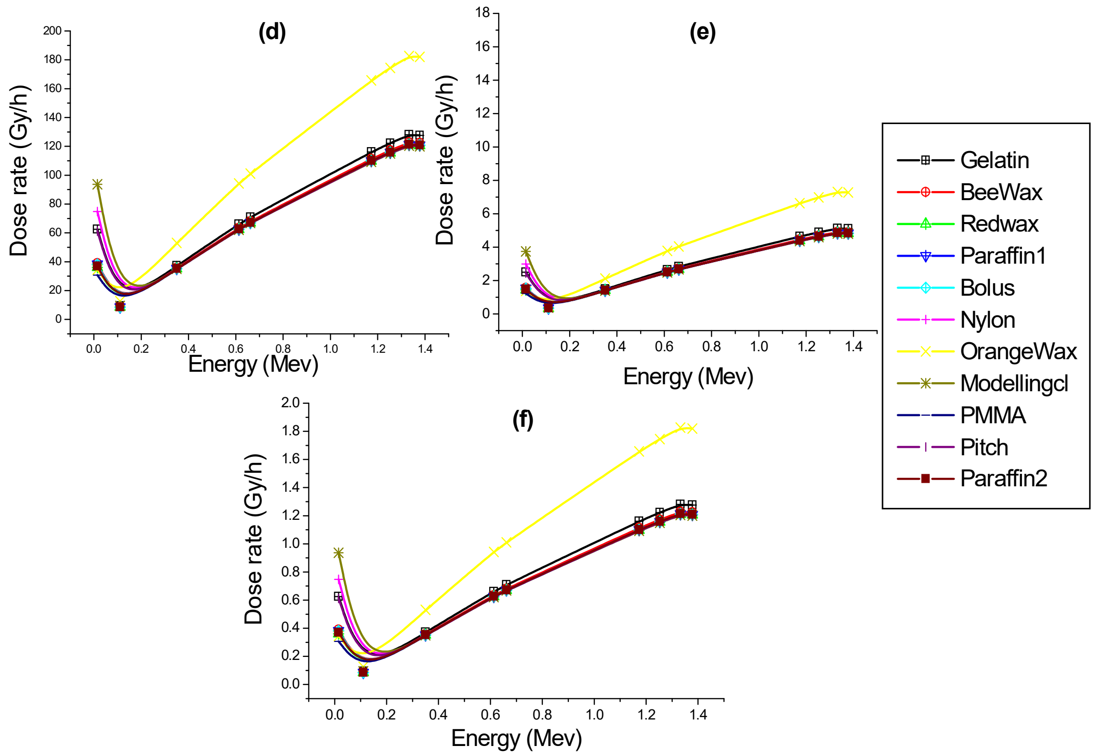

FIG. 7. Variation of dose rate tissue substitutes with photon energy (0.015<E<1.5 MeV) at three different distances of 2, 10 and 20 cm from the source.

TABLE 6. Relative dose-rate with respect to dose-rate in water, for human tissues at different photon energies, as calculated at a radial distance of 2 cm.

E (MeV)	Adipose	Skin	Muscle	Brain	Blood	Lung	Soft	Comb. bone	Cortic. bone
0.015	0.5622	0.8955	1.0222	1.0342	1.0268	1.0365	0.9183	4.2234	5.8209
0.1104	0.9643	0.9824	0.9973	1.0061	0.9981	0.9987	0.9886	1.4248	1.6324
0.35	1.0067	0.9900	0.9914	0.9989	0.9911	0.9906	0.9935	0.9655	0.9540
0.613	1.0067	0.9898	0.9910	0.9986	0.9908	0.9903	0.9932	0.9563	0.9407
0.6616	1.0046	0.9890	0.9906	0.9982	0.9905	0.9899	0.9924	0.9551	0.9398
1.173	1.0066	0.9897	0.9905	0.9985	0.9908	0.9902	0.9932	0.9542	0.9378
1.2529	1.0067	0.9897	0.9910	0.9985	0.9908	0.9902	0.9932	0.9542	0.9377
1.3325	1.0067	0.9898	0.9909	0.9985	0.9908	0.9902	0.9932	0.9541	0.9377
1.3782	1.0066	0.9898	0.9910	0.9985	0.9908	0.9902	0.9932	0.9541	0.9377

TABLE 7. Relative dose-rate with respect to dose-rate in water, for tissue substitutes at different photon energies, as calculated at a radial distance of 2 cm.

E (MeV)	Gelatin	Bee wax	Red wax	Paraffin1	Bolus	Nylon	Orange Wax	Modeling Clay	PMMA	Pitch	Paraffin2
0.015	0.8821	0.5490	0.5092	0.5400	0.5367	1.0557	0.4869	1.3219	0.4332	0.8638	0.5212
0.1104	0.9494	0.8808	0.8642	0.8695	0.8683	0.9302	1.2809	0.9498	0.8562	0.8986	0.8682
0.35	0.9564	0.9173	0.9037	0.9060	0.9051	0.9072	1.3644	0.9014	0.9029	0.9025	0.9066
0.613	0.9563	0.9169	0.9034	0.9056	0.9047	0.9059	1.3648	0.9003	0.9025	0.9021	0.9063
0.6616	0.9555	0.9149	0.9012	0.9037	0.9028	0.9044	1.3613	0.9002	0.9001	0.9014	0.9042
1.173	0.9563	0.9170	0.9035	0.9057	0.9048	0.9057	1.3647	0.9001	0.9026	0.9021	0.9064
1.2529	0.9563	0.9170	0.9035	0.9057	0.9048	0.9057	1.3646	0.9001	0.9026	0.9021	0.9064
1.3325	0.9563	0.9170	0.9035	0.9057	0.9048	0.9057	1.3646	0.9002	0.9026	0.9021	0.9064
1.3782	0.9562	0.9170	0.9035	0.9057	0.9048	0.9057	1.3646	0.9002	0.9026	0.9022	0.9064

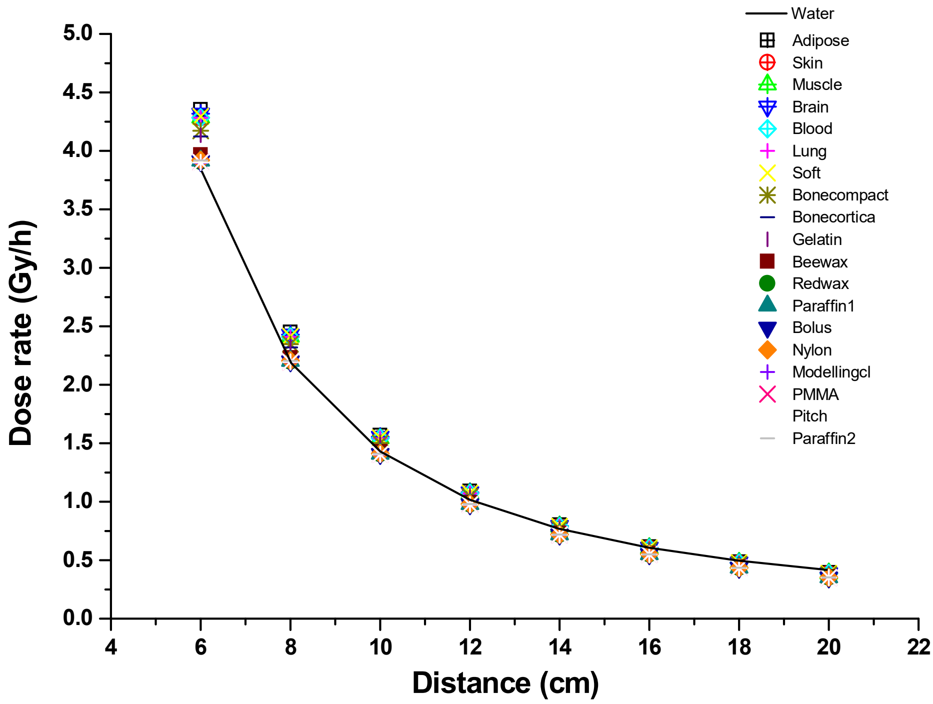

FIG. 8. Behavior of all samples and water at different radial distance from source. The results are too similar to be separable in the plot.

However, composition effect and higher dose-rate differences of some tissues compared to the others can be explained by considering differences in the equivalent atomic number, Z_{eq}, and mass energy absorption coefficient of the tissues and that of water. These factors have similar values, at higher photon energies, so that values around 1 for relative dose with respect to water can be predicted for all tissues. To examine and compare the tissue substitutes, therefore, calculation of fractional differences in their absorbed dose-rate is required, as presented in Table 8. The dose-rate in human tissues and tissue substitutes are compared for photon energies emitted by ^{137}Cs, ^{60}Co and ^{192}Ir sources. It can be seen from the table that gelatin is a good tissue substitute for compact and cortical bone tissues in the energy range (0.3-1.5 MeV). Bee wax and Paraffin2 also simulate cortical bone for the same energy range, with fractional difference of less than 5%. Orange wax, on the other hand, is out of the comparison process since it showed a fractional difference of more than 40% with any other tissue. However, for a complete formulation of tissue equivalence for a wide range of applications, the results should be combined with those obtained in the previous section, when Z_{eq} of the selected tissues were compared in the extended energy range. The best or the highest tissue equivalence is reached if its Z_{eq} and dose-rate values match as closely as possible to that of the corresponding human tissue.

TABLE 8. Fractional difference in dose-rate in human tissues and tissue substitutes for three brachytherapy source, as calculated at a radial distance of 2 cm.

Sources		Gelatin	Bee wax	Red wax	Paraffin1	Bolus	Nylon	Orange Wax	Model. Clay	PMMA	Pitch	Paraffin2
		Fractional difference (%)										
^{192}Ir	Adipose	4.9914	8.8871	10.2308	10.0099	10.0983	9.8884	35.5266	10.4544	10.3185	10.3537	9.9383
	Skin	3.3856	7.3472	8.7136	8.4890	8.5789	8.3655	37.8171	8.9409	8.8028	8.8387	8.4162
	Muscle	3.5175	7.4738	8.8382	8.6140	8.7037	8.4906	37.6290	9.0653	8.9273	8.9631	8.5413
	Brain	4.24855	8.1751	9.5291	9.3067	9.3958	9.1843	36.5857	9.7546	9.6176	9.6531	9.2344
	Blood	3.4960	7.4534	8.8181	8.5939	8.6837	8.4705	37.6592	9.0453	8.9073	8.9431	8.5211
	Lung	3.4947	7.4517	8.8173	8.5932	8.6842	8.4695	37.6599	9.0437	8.9061	8.9434	8.5209
	Soft	3.7217	7.6699	9.0313	8.8078	8.8973	8.6846	37.3372	9.2581	9.1204	9.1561	8.7351
	Bone compact	0.93108	4.9933	6.3944	6.16416	6.2568	6.0374	41.3185	6.6275	6.4859	6.5227	6.0894
	Bone cortical	0.2586	3.8524	5.2703	5.0373	5.1305	4.9090	43.0155	5.5063	5.3628	5.4001	4.9616

Sources		Gelatin	Bee wax	Red wax	Paraffin1	Bolus	Nylon	Orange Wax	Model. Clay	PMMA	Pitch	Paraffin2
Fractional difference (%)												
^{137}Cs	Adipose	5.0046	8.9045	10.2482	10.0271	10.115	10.0263	35.5622	10.5807	10.3364	10.38309	9.9565
	Skin	3.3828	7.4943	8.8792	8.6277	8.7187	8.5549	37.6398	8.9838	8.9941	8.8632	8.5771
	Muscle	3.5352	7.6402	9.0229	8.7718	8.8627	8.6991	37.4227	9.1274	9.1376	9.0069	8.7212
	Brain	4.2678	8.3417	9.7138	9.4646	9.554	9.3925	36.3792	9.8174	9.8276	9.6979	9.4143
	Blood	3.5257	7.6311	9.0139	8.7628	8.8536	8.6901	37.4364	9.1183	9.1286	8.9979	8.7121
	Lung	3.4727	7.5804	8.9640	8.7127	8.8036	8.6399	37.5118	9.06848	9.07883	8.9478	8.6620
	Soft	3.7174	7.8146	9.1947	8.9441	9.0347	8.8715	37.1633	9.2989	9.3092	9.1787	8.8935
	Bone compact	0.0461	4.2114	5.6454	5.3849	5.4792	5.3095	42.5247	5.7537	5.7643	5.6287	5.3324
	Bone cortical	1.6695	2.6570	4.1142	3.8496	3.9454	3.7730	44.8374	4.2243	4.2352	4.0974	3.7962
Fractional difference (%)												
^{60}Co	Adipose	4.88692	8.9345	10.2978	10.0502	10.140	9.9785	35.4971	10.4008	10.4109	10.2820	10.000
	Skin	3.3842	7.3506	8.7172	8.4924	8.5822	8.4916	37.8746	9.0555	8.8070	8.8545	8.4206
	Muscle	3.5006	7.4623	8.8273	8.6027	8.6924	8.6019	37.7084	9.1651	8.9169	8.9641	8.5310
	Brain	4.2301	8.1618	9.5165	9.2937	9.3826	9.2929	36.6672	9.8518	9.6055	9.6525	9.2225
	Blood	3.4821	7.4446	8.8098	8.5853	8.6749	8.5845	37.7345	9.1478	8.8995	8.9469	8.5135
	Lung	3.429	7.3931	8.7596	8.5349	8.6246	8.5341	37.8104	9.0977	8.8493	8.8968	8.4632
	Soft	3.7140	7.6670	9.0289	8.8049	8.8944	8.8041	37.4036	9.3661	9.1184	9.1657	8.7334
	Bone compact	0.2191	3.8952	5.3128	5.0796	5.1727	5.0788	43.0166	5.6637	5.4059	5.4551	5.0051
	Bone cortical	1.6695	2.6570	4.1142	3.8497	3.9453	3.7730	44.8375	4.2243	4.2352	4.097	3.7962

4. Conclusions

- Comprehensive investigations of the gamma-ray attenuation and absorption parameters, the equivalent atomic number and the absorbed dose rate should be carried out to examine tissue substitutes and the results should be compared to those of corresponding human tissues for the useful photon energy range.
- Study of a single parameter will not be enough to represent the structure of a composite material and its behavior in relation to photon interactions.
- Material linear or mass attenuation coefficient cannot be used to determine the amount of energy deposited or absorbed by it but, its mass-energy absorption coefficient has to be introduced to account for that.
- The results obtained suggested that the best material tissue equivalence is reached when Z_{eq} and dose-rate values of the material match closely to that of the corresponding human tissue of interest.

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