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Total mass attenuation coefficient evaluation of ten materials commonly used to simulate human tissue

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Abstract. To study the doses received by patient submitted to ionizing radiation, several materials are used to simulate the human tissue and organs. The total mass attenuation coefficient is a reasonable way for evaluating the usage in dosimetry of these materials. The total mass attenuation coefficient is determined by photon energy and constituent elements of the material. Currently, the human phantoms are composed by a unique material that presents characteristics similar to the mean proprieties of the different tissues within the region. Therefore, the phantoms are usually homogeneous and filled with a material similar to soft tissue. We studied ten materials used as soft tissue-simulating. These materials were named: bolus, nylon®, orange articulation wax, red articulation wax, PMMA, modelling clay, bee wax, paraffin 1, paraffin 2 and pitch. The objective of this study was to verify the best material to simulate the human cerebral tissue. We determined the elementary composition, mass density and, therefore, calculated the total mass attenuation coefficient of each material. The results were compared to the values established by the International Commission on Radiation Units and Measurements – ICRU, report n° 44, and by the International Commission on Radiation Protection – ICRP, report n° 89, to determine the best material for this energy interval. These results indicate that new head phantoms can be constructed with nylon®.

1. Introduction

To study the doses received by patient submitted to ionizing radiation, several materials are used to simulate the human tissue and organs for long time [1]. These materials are named tissue equivalent materials. Tissue equivalent materials have been often used in diagnostic and therapeutic radiology [2-4]. In the energy interval 10 keV to 150 keV (diagnostic radiology), electrons are ejected through X-ray photons interactions with the matter. The presence of this interstitial defect increases proportionality with the total mass attenuation coefficient. The total mass attenuation coefficient can be calculated through the photon energy and constituent elements of the material [2,5]. The total

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mass attenuation coefficient is a reasonable way for evaluating the usage in dosimetric applications of these materials.

The phantoms are usually homogeneous and filled with a material similar to soft tissue. In diagnostic radiology, acrylic (PMMA) is the most equivalent tissue material used. Nowadays, two acrylic phantoms are used in the CT dosimetry. They are used for simulating the patient's head and the patient's abdomen. To perform dosimetric procedures in CT is extremely important due the high doses delivered in these examinations [6].

The ICRU n° 44 has compiled the results of various studies about the utilization of tissue equivalent materials in radiodiagnostic and radiotherapy applications. The report brings the total mass attenuation coefficients, and other quantities, calculated in the X-ray energy range of 1 keV to 50 MeV. Especially in radiodiagnostic applications (10 to 150 keV), materials should have attenuation properties substantially similar from those of body tissues, since photoelectric effect is much observed [3].

Jones *et al* have developed tissue-equivalent materials for simulating the soft, lung and bone tissue of newborn, children and adult patients in CT examinations [2]. These materials were compared with the reference materials found in ICRU n° 44.

We studied ten materials often used as soft tissue-simulating. These materials were named: bolus, nylon®, orange articulation wax, red articulation wax, PMMA, modelling clay, bee wax, paraffin 1, paraffin 2 and pitch. The objective of this study was to verify which the best material to simulate the human cerebral tissue, in terms of total mass attenuation coefficient and mass density in the energy range of 10 to 150 keV. The results were compared to the values established by the International Commission on Radiation Units and Measurements – ICRU, report n° 44 [3], and International Commission on Radiation Protection – ICRP, report n° 89 [4].

2. Materials and Methods

The materials analized here were bolus, nylon®, orange articulation wax, red articulation wax, PMMA, modelling clay, bee wax, paraffin 1, paraffin 2 and pitch. All are commercially available. Before calculating the total mass attenuation coefficient, it was necessary obtain the elemental compositions (mass fraction of each element). For obtaining the mass fraction of the hydrogen (H), carbon (C), nitrogen (N) and sulphur (S) contained in each sample, it was used the Flash EA 1112 Series CHNS analyzer. The mass fraction remaining in each sample was considered as oxygen (O). These materials are basically composed of these elements (H, C, O, N, S) [2-4].

The total mass attenuation coefficient can be obtained through the total cross section for photons by the rule given in Hubbell (2006):

$$\frac{\mu}{\rho} = \frac{\sigma_{tot}}{m_u A} \quad (1)$$

where μ/ρ is the total mass attenuation coefficient, σ_{tot} is the total cross section for photons, m_u is the atomic mass unit and A is the relative atomic mass of the material.

To calculate the total mass attenuation coefficient, the software WinXCom was utilized [7-9]. The mass fraction of each element was insered as input parameter and WinXCom has calculated the total mass attenuation coefficient through the available tables in Hubbel and Seltzer [10]. The mass density of each sample was calculated using the Archimedean principle.

3. Results and discussion

3.1. Mass density

The table 1 shows the results of the mass density. It also is showed the percentage difference of each material in relation to ICRU's brain and ICRP's brain, respectively. The mass density obtained for each material indicated a good concordance with the mass density of the ICRU's brain and ICRP's brain. The major absolute value of the percentage difference was 23.6% for modelling clay in relation to ICRP's brain. The better values for mass density were encountered for the bee wax.

Table 1. Mass density of the tissue material equivalent and percentage differences in relation to ICRU's brain and ICRP's brain.

Tissue equivalent materials	Mass density (g/cm^3)	Percentage difference (%) (substitute/ICRU's brain)	Percentage difference (%) (substitute/ICRP's brain)
Bee wax	0.964	-7.3	-6.4
Red articulation wax	0.911	-12.4	-11.6
Paraffin 1	0.959	-7.8	-6.9
Bolus	1.112	6.9	8.0
Nylon®	1.160	11.5	12.6
Orange articulation wax	0.931	-10.5	-9.6
Modelling clay	1.273	22.4	23.6
PMMA	1.178	13.3	14.4
Pitch	1.148	10.4	11.5
Paraffin 2	0.918	-11.7	-10.9
ICRU's brain[a]	1.040	c	c
ICRP's brain[b]	1.030	c	c

[a] ICRU reference [3].
[b] ICRP reference [4].
[c] not applicable.

3.2. Total mass attenuation coefficient

The table 2 shows the elemental compositions obtained for each material. The results for each material were used as input data on the WinXcom software. Thus, the total mass attenuation coefficient for each material was calculated.

The total mass attenuation coefficient for each material was divided by the total mass attenuation coefficient of the human brain (ICRU and ICRP) in the energy range of 10 to 150 keV. The figure 1 and figure 2 show the ratios of total mass attenuation coefficient for the modelling clay and the nylon®, respectively. The table 3 shows the mean and the standard deviation of the ratios between each material and the human brain (ICRU and ICRP). In this way, the material to simulate the human cerebral tissue will be indicated by the mean that presents the value closer to 1. Thus, modelling clay and nylon® present good agreement with human brain in terms of total mass attenuation coefficient. Nylon® presents also good agreement in terms of mass density. For this reason, it can be concluded that, among the materials evaluated in this work, nylon® is the most indicated for simulating the human cerebral tissue. Although the mass density suggests the bee wax as substitute material of the human brain, it did not present good agreement in the total mass attenuation coefficient, which is the more indicated quantity for dosimetric comparisons [2-5].

Table 2. Elemental composition for tissue equivalent materials.

Tissue equivalent materials	C (%)	N (%)	S (%)	H (%)	O (%)
Bee wax	75.25	8.42	0.19	1.87	14.27
Red articulation wax	80.17	11.23	0.09	0.36	8.14
Paraffin 1	81.73	0.74	0.10	0.61	16.81
Bolus	82.22	0.78	0.09	0.50	16.41
Nylon®	59.49	4.34	3.96	0.63	31.58
Orange articulation wax	82.00	7.37	0.08	2.73	7.82
Modelling clay	19.76	0.86	3.55	0.00	75.83
PMMA	94.96	4.71	0.10	0.24	0.00
Pitch	42.18	0.42	0.46	0.19	56.76
Paraffin 2	79.61	9.63	0.14	0.68	9.94

Table 3. Mean of the ratios of total mass attenuation coefficients of the tissue equivalent materials in relation to ICRU's brain and ICRP's brain, respectively.

Tissue equivalent materials	Mean of the Ratio (substitute/ICRU's brain)	Mean of the Ratio (substitute/ICRP's brain)
Bee wax	0.782 ± 0.138	0.773 ± 0.148
Red articulation wax	0.760 ± 0.147	0.752 ± 0.156
Paraffin 1	0.772 ± 0.137	0.764 ± 0.147
Bolus	0.771 ± 0.138	0.762 ± 0.148
Nylon®	0.995 ± 0.040	0.941 ± 0.037
Orange articulation wax	0.756 ± 0.163	0.756 ± 0.173
Modelling clay	1.046 ± 0.136	1.029 ± 0.118
PMMA	0.732 ± 0.173	0.725 ± 0.182
Pitch	0.885 ± 0.022	0.873 ± 0.042
Paraffin 2	0.766 ± 0.144	0.758 ± 0.154

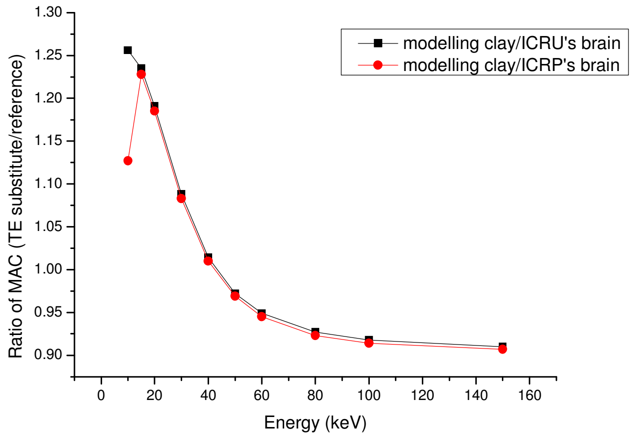

Figure 1. Ratio of total mass attenuation coefficients (MAC) for the modelling clay to their corresponding reference values (ICRU's brain and ICRP's brain).

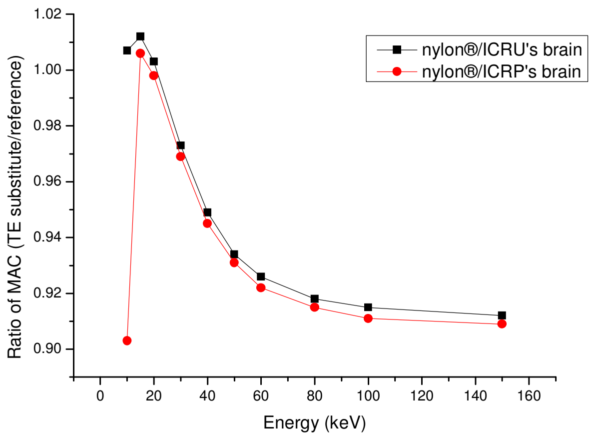

Figure 2. Ratio of total mass attenuation coefficients (MAC) for the nylon® to their corresponding reference values (ICRU's brain and ICRP's brain).

The figures show that the values of μ/ρ differ of their corresponding values mainly in low energies (10 up to 40 keV). This is due to the difference of elemental composition that influences the photoelectric effect which is the major responsible by the total mass attenuation coefficient in this energy range.

4. Conclusions

A more reasonable way for evaluating tissue equivalent materials is the total mass attenuation coefficient. The total mass attenuation coefficients results indicated that the modelling clay and nylon® could be used as tissue equivalent of human brain. But, only nylon® has found good agreement with the human brain (ICRU and ICRP) in terms of total mass attenuation coefficient and mass density. Therefore, the utilization of this material for constructing human phantoms is a good and low-cost alternative. For example, a nylon® CT head phantom has been constructed and its cost has been about fifteen times less than acrylic CT head phantom actually used in dosimetry.

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