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Usage of attenuation coefficients of some tissue-equivalent materials

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Abstract: The total attenuation coefficients of 11 biological targets against photon energies were plotted within the energy range 1–10 MeV. From these plots a possible equation describing the relationship between photon energy and the total attenuation coefficient was derived. The suggested equation is $\mu/\rho = 0.0696/\sqrt{E}$. To test the validity of the equation and to compare the results of the total attenuation coefficients of 3 tissue-equivalent materials (bolus, rice grains, and boiled rice) that could not be determined before, they were determined experimentally by using X-rays produced at 6 MV and 18 MV. The results of the experiment show a relatively good match with the computed values using the suggested equation. It is possible to conclude that 1) the suggested equation is a practical way to define the total attenuation coefficients of biological tissue or tissue-equivalent materials and 2) the attenuation coefficient is one of the most important to determine the absorbed dose by patients and so they should be worked out experimentally before treatment.

Key words: Attenuation coefficients, radiotherapy, tissue equivalent materials

1. Introduction

In radiotherapy applications a reasonable way to plan the doses received by tissue is to use the total attenuation coefficient (TAC) of tissue-equivalent material. Tissue-equivalent materials are commonly used for a variety of purposes in radiotherapy applications. One of the most important ways of testing is to determine the validity of tissue-equivalence. Moreover, the total attenuation coefficient of materials is vitally important in calculating the effect of radiation energy on the patient or in implementing radiation shielding processes. Although in the literature it is possible to see many works related to TAC [1–4], the TAC data of biological samples are still limited.

In most medical physics applications involving photons at least one of the mechanisms by which photons interact with matter plays an important role. Some properties of these interactions are that, in general, the photoelectric attenuation coefficient is directly proportional to the atomic number in order of Z^5 whereas its dependence on photon energy approximates an inverse cube [5]. The photoelectric effect is the dominant mode of low-energy photons; Compton scattering occurs for attenuation from intermediate energies; pair production is the creation of a positive electron and a negative electron. It occurs when a photon interacts with a nucleus and it dominates at high energies ($\geq$1.022 MeV). As a result, the total attenuation coefficient μ (cm^{-1}) is given by following equation (Bouger–Lambert–Beer law):

$$I = I_0 \exp(-\mu x) \quad (1)$$

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in which x is the thickness (cm) of the material; I_0 is the intensity of the incident beam of X-rays; I is the intensity of the transmitted beam [6]. In this study because the dose absorbed by the target is also proportional to intensity the following equation was used:

$$D = D_0 \exp(-\mu x), \tag{2}$$

where D_0 is the primary dose given to the target and D is the transmitted dose through x thickness.

In this work the relationship between the TAC of tissue-equivalent materials and biological tissues was investigated as a function of photon energy. The total attenuation coefficients for adipose tissue, water, muscle, brain, 2 different soft tissues, blood, breast tissue, testis, eye lens, and lung tissue (Table 1) were evaluated for photon energies in the range 1–10 MeV. TAC values versus X-ray energies were plotted. In addition, the TAC values of bolus, rice grains, and boiled rice, which were used as tissue-equivalent materials in radiotherapy, were experimentally measured and compared to the results of biological materials.

Table 1. The relation of total attenuation coefficients with the photon energy in the range of 1–10 MeV.

Target*	$\mu/\rho = AE^{-b}$	r^2
Adipose tissue (ICRU 44)	$0.07 \times E^{-0.52}$	0.999
Water (liquid)	$0.07 \times E^{-0.51}$	0.998
Muscle (skeletal, ICRU 44)	$0.069 \times E^{-0.51}$	0.999
Brain (gray/white, ICRU 44)	$0.07 \times E^{-0.51}$	0.999
Tissue, soft (ICRU-4 component)	$0.0697 \times E^{-0.51}$	0.999
Tissue, soft (ICRU-44)	$0.0697 \times E^{-0.51}$	0.999
Blood	$0.069 \times E^{-0.51}$	0.999
Brest tissue	$0.07 \times E^{-0.51}$	0.999
Testis	$0.07 \times E^{-0.51}$	0.999
Eye lens	$0.0697 \times E^{-0.51}$	0.999
Lung tissue	$0.069 \times E^{-0.51}$	0.999

* The contents of the materials were taken from ICRU-44. TAC values were calculated using the input data on the XCOM software.

2. Experimental

In the experiments dose measurements were performed using an electrometer (PTW Unidos brand, model number T10008, series number 80616) and an ion chamber (parallel plate marked PTW, model number TM34045, series number 679). The density of the solid-water phantom RW3 was 1.045 g/cm^3 and its electron density was 3.43×10^{23} e/cm^3. It was made of white polystyrene containing 2% TiO_2. It consists of 29 plates with dimensions of 40 × 40 cm^2; 1 plate of 1-mm, 2 plates of 2-mm, 1 plate of 5-mm, and 25 plates of 10-mm thickness. The linear accelerator (LINAC) used to irradiate was a Siemens Oncor Impression (San Francisco, CA, USA). All the experimental measurements were performed using X-rays produced at 6 MV and 18 MV. The experimental processes were performed on the table on which the patients were exposed to X-rays.

The bolus material was a solid form homogeneous gel. It is commercially available. Its density is 1.03 g/cc. Bolus materials generally consist of 40% Na, 50% paraffin, and 50% wax. The boiled rice was produced by boiling rice grains in water and then drying. It was used by increasing its thickness from 1 cm to 12 cm.

All the experimental measurements were performed at pressure of 902.4 mbar and temperature of ~20.4 °C.

3. Results and discussion

3.1. TAC values of some biological materials

The total attenuation coefficients of the 10 biological structures (whole blood, skeletal muscle, brain, soft tissue (ICRU 44), testis, eye lens, lung tissue, adipose tissue, breast tissue, soft tissue (ICRU-4 component) and water (liquid)) were calculated for the X-rays in the 1–10 MeV energy range using data provided by NIST via their online XCOM database [7,8]. The TAC values versus photon energy were plotted and an acceptable equation was derived by curve-fitting (Table 1). Figure 1 shows a sample graph plotted for water and lung. The TAC values of the 10 biological targets and water were shown to have the same TAC values for the same energy. The difference between them lies in the range 0%–1%. Therefore, as can be seen from the data in Table 1, the relationship between TAC and photon energy was given as

$$\mu/\rho = 0.0696\frac{1}{\sqrt{E}} \tag{3}$$

where μ/ρ is total mass attenuation coefficient in cm^2/g and E is energy in MeV.

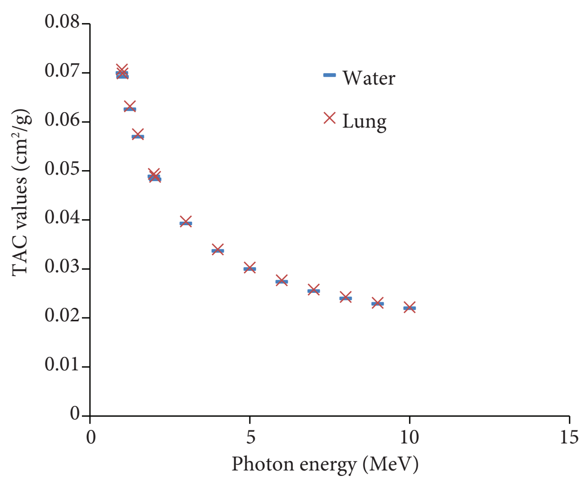

Figure 1. Total attenuation coefficients for water and lung versus x-ray energy (TAC values were calculated using the input data on the XCOM software).

3.2. Experimental TAC values

3.2.1. TAC values of solid-water phantom

Comparison of the TAC values of phantom materials that can be used as tissue-equivalent materials with that of a solid water phantom that was used for the calibration process in radiotherapy is important in terms of deciding which phantom material is appropriate for use. The TAC values of the solid phantom were evaluated using Eq. (3). They are 0.0492 cm^2/g for 2 MeV and 0.0284 cm^2/g for 6 MeV.

The experimental studies on the TAC values of the same solid water phantom were carried out by Karaman [9,10] in the same medical unit and under the same conditions as our study. The reported values are 0.042 $\pm$ 0.003 cm^2/g and 0.0263 $\pm$ 0.01 cm^2/g for 2 MeV and 6 MeV, respectively.

As is known, the X-rays from LINAC are not monoenergetic. The electron energy is converted into a spectrum of X-ray energies with maximum energy equal to the incident electron energy [6]. In the present study

X-rays produced at 6 MV and 18 MV were used. Their average energies are 2 MeV and 6 MeV; the maximum energies are 6 MeV and 18 MeV.

3.2.2. The TAC values of tissue-equivalent materials

The experimental algorithm is as follows: the initial radiation dose D_0 was measured and then the dose measurements were performed for materials from 1 cm to 10 cm by increasing the thickness by 1 cm. The semilogarithmic dose-thickness graph was plotted (Figures 2–4) and its tangent determined.

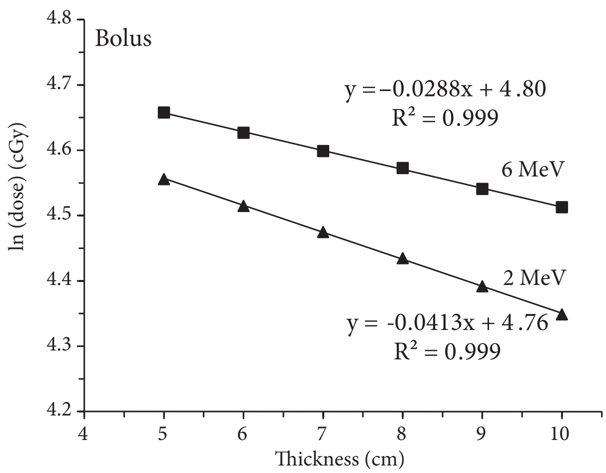

Figure 2. Total mass attenuation coefficient of bolus for x-rays at 2 MeV and 6 MeV.

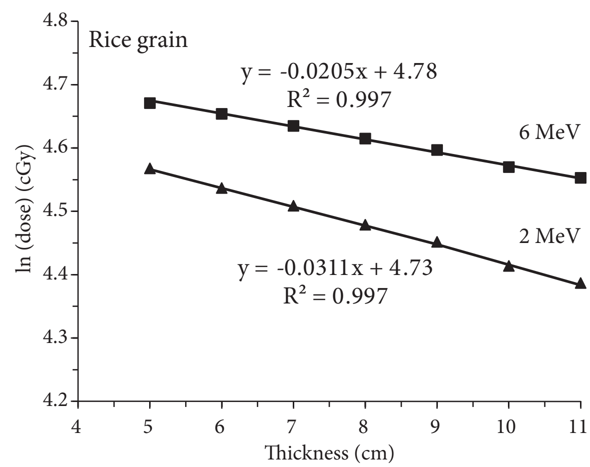

Figure 3. Total mass attenuation coefficient of rice grain for x-rays at 2 MeV and 6 MeV.

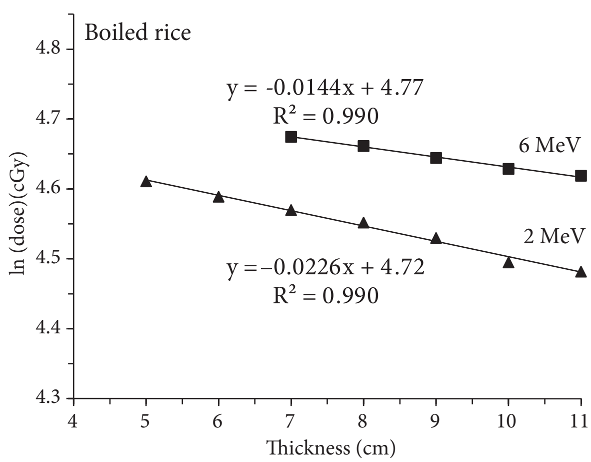

Figure 4. Total mass attenuation coefficient of boiled rice for x-rays at 2 MeV and 6 MeV.

Figures 2–4 show the experimental TAC values for the bolus, rice grains, and boiled rice, respectively. They are listed in Table 2 to compare the results with others. When the experimental TAC value of the solid water phantom (0.042 ± 0.01 cm^2/g) was compared with that of the bolus (0.0401 ± 0.01 cm^2/g) the difference between them is ~4.5% for 2 MeV. A similar result is found for 6 MeV: the TAC values of the solid phantom and bolus are 0.0263 ± 0.01 cm^2/g and 0.0271 ± 0.01 cm^2/g, respectively. The difference is only ~3%. Moreover, for rice grains it was 0.0451 ± 0.01 cm^2/g at 2 MeV, with the deviation being ~7%. For 6 MeV the deviation was ∼11%. One of the reasons for the discrepancy could be that the X-rays produced by LINAC have a continuous energy spectrum. It can be concluded that the bolus and rice grains are relatively acceptable materials for use as a tissue equivalent. However, the deviation between the TAC values of boiled rice and solid water is so great (40% for 2 MeV and 39% for 6 MeV) that it should not be used as phantom material in radiotherapy. The deviations between TAC values of tissue-equivalent materials and of human tissues are nearly identical. The deviation between the experimental TAC value of the solid water used in this study and that of water (liquid) evaluated from XCOM [8] was found to be ∼11% and this is also too high for radiotherapy applications. Although rice grains are a relatively good tissue-equivalent material, boiled rice is not. The main reason for the deviation between the TAC values of water and bolus and rice grains could be that the X-rays produced from LINAC have a broad energy spectrum. The TAC values from XCOM [8] are for monoenergic X-rays.

Table 2. Total mass attenuation coefficients (μ/ρ) in cm^2/g.

Tissue-equivalent material	Potential peak 6 MV, 2 MeV	Potential peak 18 MV, 6 MeV
Bolus ($\rho = 1.03$ g/cm^3)	0.0401	0.0271
Rice grain ($\rho = 0.689$ g/cm^3)	0.0451	0.0297
Boiled rice ($\rho = 0.9$ g/cm^3)	0.0251	0.016
Solid water phantom ($\rho = 1.045$)	0.042	0.0263
Water (liquid)	0.0494	0.0277
Blood	0.0489	0.0274
Muscle skeletal (ICRU44)	0.0490	0.0274
Brain (gray/white, ICRU44)	0.0492	0.0275
Tissue soft (ICRU-4 component)	0.0489	0.0274
Testis	0.0491	0.0275
Eye lens	0.0487	0.0272
Lung tissue	0.049	0.0275
Adipose tissue	0.0494	0.0272
Breast tissue	0.0491	0.0273

As a result, it has to be noted that using the experimentally obtained TAC values of tissue substitutes should be more appropriate in dose planning studies.

4. Conclusions

The conclusions are as follows:

1) The TAC values of tissue-equivalent materials used in the field of medicine to calculate the radiation doses absorbed by patients should be experimentally determined using photons produced by LINAC used in that laboratory rather than theoretical results.

2) While rice grains are reasonably acceptable tissue equivalent materials, boiled rice is not.

3) The total mass attenuation coefficient of a biological tissue can be practically worked out using Eq. (3) for X-rays in the range 1–10 MeV.

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References

[1] Hubbell, J. H. *Phys. Med. Biol.* **1999**, *44*, R1–R22.

[2] Teli, M. T.; Mahajan, C. S.; Nathuram, R. *Radiat. Meas.* **2000**, *32*, 329–333.

[3] Hill, R. F.; Brown, S.; Baldock, C. *Radiat. Meas.* **2008**, *43*, 1258–1264.

[4] Ferreira, C. C.; Ximenes, R. E.; Garcia, C. A. B.; Vieria, J. W.; Maia, A. F. J. Phy.: Conference Series **2010**, *249*, 012029.

[5] Martin, J. E. *Physics for Radiation Protection,* 2nd ed; John Wiley & Sons: New York, NY, USA, 2011.

[6] Khan, F. M. *Physics of Radiation Therapy* Third ed. Lippincott, Williams & Wilkins: Philadelphia, PA, USA, 2003.

[7] Hubbell, J. H.; Selzter, S. M. National Institute of Standards and Technology, 1995.

[8] Berger, M. J.; Hubbell, J. H. XCOM: National Institute of Standards and Technology, Gaithersburg, MD 20899, USA, 1987, 99.

[9] Karaman, O. MSc, Gazi University, Institute of Sciences, Ankara, Turkey, 2012.

[10] Karaman, O; Tanır, A. G; Bölükdemir, M. H. *Turk. J Phys.* doi: 10.3906/fiz-1401-15.