STUDIES ON NEUTRON AND PHOTON KERMA PARAMETERS FOR HUMAN BODY ORGANS

by

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A study on neutron kerma factors and photon air-kerma for human organs is presented for neutron energy range 2.53 10^{-8} to 29 MeV and photon energy range 1 keV to 20 MeV. The human organs water equivalence for photon and neutron, is also presented. The ratio of the mass-energy absorption coefficients of human organs to water was found constant and unity above 100 keV, whereas there was a large difference for energies below 100 keV. The neutron kerma factors of human organs and water are found of same order of magnitude whereas differs for air. The neutron kerma factors of human organs and tissue substitutes were found to be equal to water for neutron energies between 63 eV and 200 keV. The skeleton-cortical bone was found to be away from water equivalence for low-energy photons and high-energy neutrons.

Key words: human organs, kerma, photon, neutron, water

INTRODUCTION

Ionizing radiation is widely applied in different areas of medical sciences including medical items sterilization, diagnostic radiology, pharmaceutical labelling, and radiotherapy [1]. In nuclear medicine, radiation provides diagnostic information about the functioning of a specific organ; also, is used for therapy and imaging using gamma camera for accurate detection of disease progression and staging in vital organs [2].

X-rays, magnetic resonance imaging (MRI), computerized tomography (CT) scan, positron emission tomography (PET) and single positron emitted computed tomography (SPECT) are image methods used in diagnostics. Nowadays, the cancer patients receive radiation dose during course of the treatment depending on the type of cancer/tumour, which is aimed to impact the tumour; however, there are organs and tissues that also receive scattered radiation. Various types of radiations (X-rays, gamma rays, and neutrons) are used for cancer treatment, wherein fast neutron therapy is found to be better compared to gamma radiation, because of large LET values [3] .To kill the same number of cancerous cells, neutrons require one third the effective dose with respect to protons [4] .

Kerma is an acronym for kinetic energy released per unit mass, defined as the sum of the initial kinetic energies of all the charged particles liberated by uncharged ionizing radiation (*i. e.*, indirectly ionizing radiation such as photons and neutrons) in a sample of matter, divided by the mass of the sample [5, 6]. It is defined by $K = \mathrm{d}E_{\mathrm{tr}}/\mathrm{d}m$, where E_{tr} is the energy transferred and m is the mass. The kinetic energy of charged particles liberated after interaction depends upon the initial energy of radiation. In case of photons, the photon energy is transferred to a medium in a two-step process. First, energy is transferred to charged particles in the medium through partial photon interaction processes (*e. g.* photoelectric effect, Compton scattering, pair production, and photodisintegration). Next, these secondary charged particles transfer their energy to the medium through atomic excitation and ionizations. However, neutron interaction has a high linear energy transfer (LET), since neutron interacts primarily via (n, p) or spallation reactions, thus it deposits a large amount of energy. Neutron therapy is superior to proton therapy for cancer treatment, because of its higher biological effectiveness, exponential cell survival and slow DNA damage.

The sensitivity of salivary gland tumours, sarcomas, and melanomas and prostate tumours is higher for neutron than that obtained with photon exposure [7].

During treatment of cancerous cells of a tumour, some healthy cells are being exposed to sub-lethal dose. Therefore, procedure for cancer treatment with radiation always considers low exposure. It has been already reported that that treatment with neutrons implies less exposure compared with treatment with pho-

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tons or electrons. The dose delivered by neutrons, required to kill the same number of cancerous cells, is approximately one third of the dose delivered by photons [8]. The importance of neutron energy deposition and energy of the generated charged particles in fast neutron therapy is described in literature [9].

Practical exposure of human organs requires exhaustive database and information regarding interaction of radiation with human organs and possible affects after exposure. The radiation interaction, energy depositions and secondary charge production, is simulated with tissue equivalent materials and phantoms. The phantom materials for simulation should be chosen after thorough investigation of physical, chemical and radiation interaction parameters.

Kerma values which are used for neutron interaction are defined for medical applications. Similarly, kerma values of photon radiation are used in dosimetry for dose evaluation. The use of the kerma factors in neutron dosimetry has been reported in the literature [10-12] .The neutron kerma factors for elements and a few materials have been reported [13], also photon kerma of alcohols and thermo-luminescent dosimeters have been reported [14, 15]. Considering wide application of photons and neutrons for diagnosis and therapy of various human body organs, it is vital to investigate the energy of secondary charged particles in human organs. The simulations and research work is carried out using tissue equivalent materials, therefore some suitable tissue materials are also studied.

The aim of this work is to calculate the photon and neutron kerma factors of vital human organs. The water equivalence of human organs and tissue substitutes, is also discussed for research and medical applications. The present study is useful for photon and neutron applications in medical practice.

MATERIAL AND METHOD

The density and the elemental composition of human organs and tissue substitutes are shown in tabs. 1 and 2 [13], respectively. These features were used for calculating the kerma parameters.

Table 1. Elemental compositions and density of human body organs

Organ or tissue	Code	Elemental composition and density												
		H	C	N	O	Na	S	Cl	P	K	Fe	Ca	Mg	I	Density [kgm^{-3}]
Adipose tissue	AdTs	11.4	59.8	0.7	27.8	0.1	0.1	0.1							950
Blood (whole)	BL	10.2	11	3.3	74.5	0.1	0.2	0.3	0.1	0.2	0.1				1060
Brain	BR	10.7	14.5	2.2	71.2	0.2	0.2	0.3	0.4	0.3					1040
Breast (mammary gland)	BT	10.6	33.2	3	52.7	0.1	0.2	0.1	0.1						1020
Cell nucleus	ClNs	10.6	9	3.2	74.2		0.4		2.6						1000
Eye lens	EyLs	9.6	19.5	5.7	64.6	0.1	0.3	0.1	0.1						1070
GI tract (intestine)	GiTt	10.6	11.5	2.2	75.1	0.1	0.1	0.2	0.1	0.1					1030
Heart (blood filled)	HT	10.3	12.1	3.2	73.4	0.1	0.2	0.3	0.1	0.2	0.1				1060
Kidney	KY	10.3	13.2	3	72.4	0.2	0.2	0.2	0.2	0.2		0.1			1050
Liver	LR	10.2	13.9	3	71.6	0.2	0.3	0.2	0.3	0.3					1060
Lung	LG	10.3	10.5	3.1	74.9	0.2	0.3	0.3	0.2	0.2					1050
Lymph	LH	10.8	4.1	1.1	83.2	0.3	0.1	0.4							1030
Muscle (skeletal)	ME	10.2	14.3	3.4	71	0.1	0.3	0.1	0.2	0.4					1050
Ovary	OY	10.5	9.3	2.4	76.8	0.2	0.2	0.2	0.2	0.2					1050
Pancreas	PS	10.6	16.9	2.2	69.4	0.2	0.1	0.2	0.2	0.2					1040
Skeleton-cartilage	SnCe	9.6	9.9	2.2	74.4	0.5	0.9	0.3	2.2						1100
Skeleton-cortical bone	SnCb	3.4	15.5	4.2	43.5	0.1	0.3		10.3			22.5	0.2		1920
Skeleton-red marrow	SnRw	10.5	41.4	3.4	43.9		0.2	0.2	0.1	0.2	0.1				1030
Skeleton-spongiosa[a]	SnSa	8.5	40.4	2.8	36.7	0.1	0.2	0.2	3.4	0.1	0.1	7.4	0.1		1180
Skeleton-yellow marrow	SnYw	11.5	64.4	0.7	23.1	0.1	0.1	0.1							980
Skin	SN	10	20.4	4.2	64.5	0.2	0.2	0.3	0.1	0.1					1090
Spleen	SP	10.3	11.3	3.2	74.1	0.1	0.2	0.2	0.3	0.3					1060
Testis	TS	10.6	9.9	2	76.6	0.2	0.2	0.2	0.1	0.2					1040
Thyroid	TD	10.4	11.9	2.4	74.5	0.2	0.1	0.2	0.1	0.1				0.1	1050

Table 2. Elemental compositions and density of tissue substitutes

Tissue equivalent	Elemental composition and density												
	H	C	N	O	F	Ca	Cl	Na	S	K	P	I	Density [kgm^{-3}]
A150	10.1	77.7	3.5	5.2	1.7	1.8							1120
BR12	8.7	69.9	2.4	17.9		1	0.1						970
RM/G1	10.2	9.4	2.4	77.4			0.2	0.1	0.1	0.2			1070
TH/L2	10	13.6	2.2	73.5			0.1	0.2		0.2	0.1	0.06	1080

Photon kerma

Assuming the energy flux of mono-energetic photons ψ [Jm^{-2}] that is perpendicular to an area A in a medium with a mass energy-absorption coefficient, μ_{en}/ρ. The energy transferred to charged particles in the volume over a short distance dx, behind the area, is $\psi A \mu_{\mathrm{en}}$ dx. Since the mass in the volume with the density ρ is ρAdx, the kerma is given by

$$K \quad \frac{\psi A \mu_{\mathrm{en}} \mathrm{d}x}{\rho A \mathrm{d}x} \quad \psi \frac{\mu_{\mathrm{en}}}{\rho} \tag{1}$$

Therefore, the kerma is the product of the energy flux and the mass energy-absorption coefficient. The kerma of any tissue relative to air is defined by

$$K \quad \frac{\left(\frac{\mu_{\mathrm{en}}}{\rho}\right)_{\mathrm{Tissue}}}{\left(\frac{\mu_{\mathrm{en}}}{\rho}\right)_{\mathrm{Air}}} \tag{2}$$

In order to compute kerma relative to air, the values of mass energy-absorption coefficient, μ_{en}/ρ, for air and the selected tissue were calculated by mixture rule [16]

$$\frac{\mu_{\mathrm{en}}}{\rho} \quad {}_{\mathrm{i}} \, w_{\mathrm{i}} \left(\frac{\mu_{\mathrm{en}}}{\rho}\right)_{i} \tag{3}$$

Here, w_{i} and $(\mu_{\mathrm{en}}/\rho)_{\mathrm{i}}$ are the weight fraction and the mass energy-absorption coefficient of the ith element present in a tissue. The values of $(\mu_{\mathrm{en}}/\rho)_{\mathrm{i}}$ have been taken from the compilation report of [17].

Neutron kerma

The dissipation of neutron energy in a medium is a two-step process. In the first step, neutrons transfer energy to the atomic nuclei producing secondary charged particles. In the second step, the secondary charged particles traverse the medium, giving up the energy to the atoms and molecules by excitation and ionization. The kerma due to neutrons interacting with a medium was calculated

$$K \quad \overset{E_{\max}}{\underset{E_{\min}}{\quad}} \Phi_{\mathrm{E}}(E) k_{\mathrm{T}}(E) \mathrm{d}E \tag{4}$$

where $\Phi E(E)$ is the neutron flux spectrum and $k_{\mathrm{T}}(E)$ – the neutron kerma factor for the compound or mixture. $k_{\mathrm{T}}(E)$ was calculated using the KERMA program by eq. [18]

$$k_{\mathrm{T}}(E) \quad \underset{\mathrm{i}}{\quad} w_{\mathrm{i}} k(E)_{\mathrm{i}} \tag{5}$$

Here, w_{i} is the weight fraction of the ith element in the tissue substitute and $k(E)_{\mathrm{i}}$ is the neutron kerma factor of i^{th} element in the compound or composite material. Kerma factors for elements are from [19].

The water equivalence of a tissue for neutron interaction was calculated

$$\frac{K_{\mathrm{Tissue}}}{K_{\mathrm{Water}}} \quad \frac{K_{\mathrm{T}}(E)_{\mathrm{Tissue}}}{K_{\mathrm{T}}(E)_{\mathrm{Water}}} \tag{6}$$

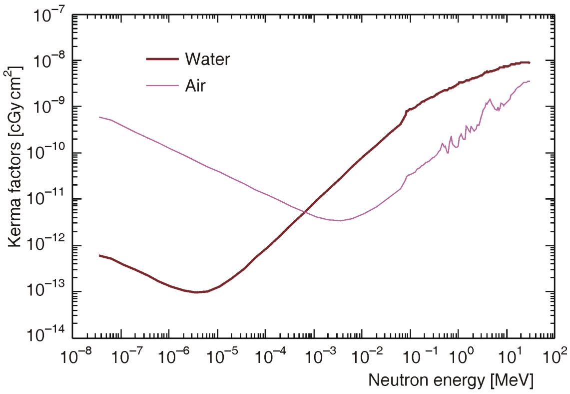

Figure 1. Neutron kerma factors of water and air

In fig. 1, the neutron kerma factors of water and air, are shown [19].

RESULTS AND DISCUSSION

The neutron kerma parameters of human organs and tissue substitutes for 2.53 10^{-8} to 29 MeV neutrons energies are shown in figs. 2-8. While in figs. 9-15, photon air-kerma of human organs and tissue substitutes for energies of 1 keV to 20 MeV, are presented.

Ratio of mass-energy absorption coefficients of human organs and tissue substitutes to water are

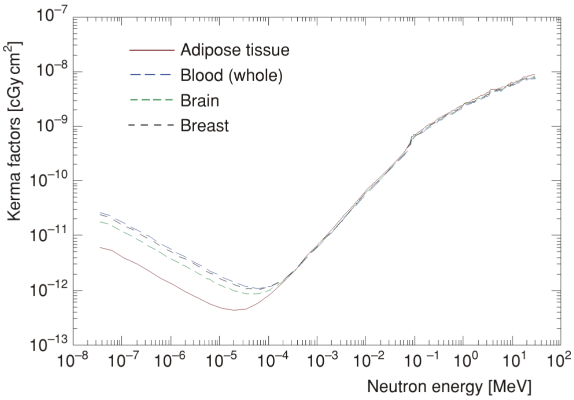

Figure 2. Neutron kerma factors for adipose tissue, blood (whole), brain, and breast

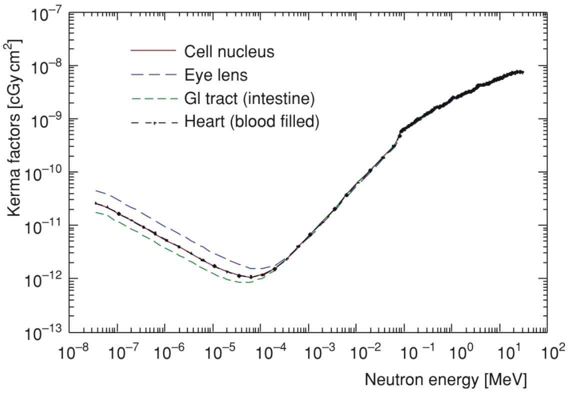

Figure 3. Neutron kerma factors for cell nucleus, eye lens, GI tract, and heart (blood filled)

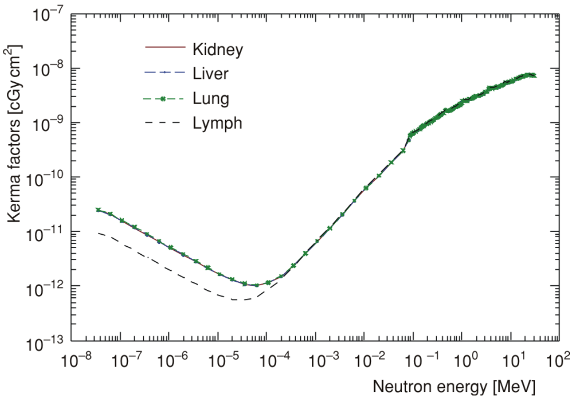

Figure 4. Neutron kerma factors for kidney, liver, lung, and lymph

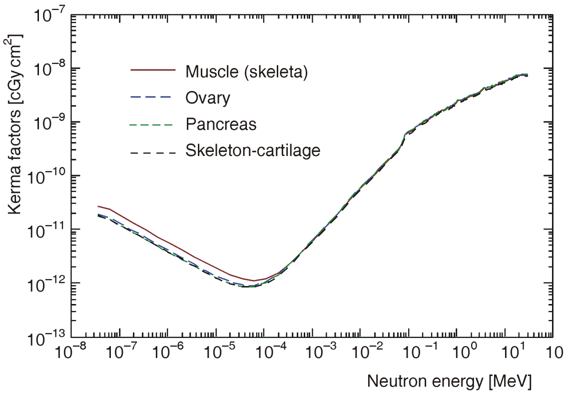

Figure 5. Neutron kerma factors for muscle (skeleton), ovary, pancreas, and skeleton-cartilage

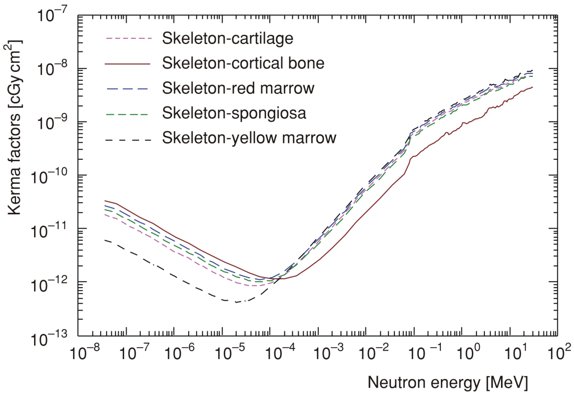

Figure 6. Neutron kerma factors for skeleton-cartillage, skeleton-cortical bone, skeleton-red marrow, skeleton-spongiosa, and skeleton-yellow marrow

shown in fig. 16. The ratio merges to unity above photon energy of 100 keV for all the human organ and tissue substitutes. However, at about 30 keV (fig. 16), the ratio reaches up to 7 for skeleton cortical bone (SnCb) and almost 3 for skeleton-spongiosa (SnSa), whereas other's near to unity.

Neutron kerma factors (NKF) of human organs and tissue substitutes and water are shown in fig. 17.

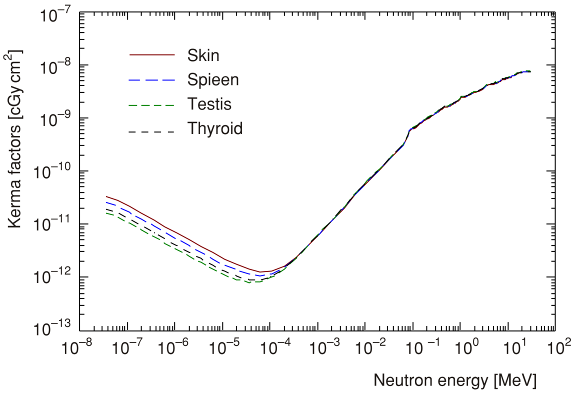

Figure 7. Neutron kerma factors for skin, spleen, testis, and thyroid

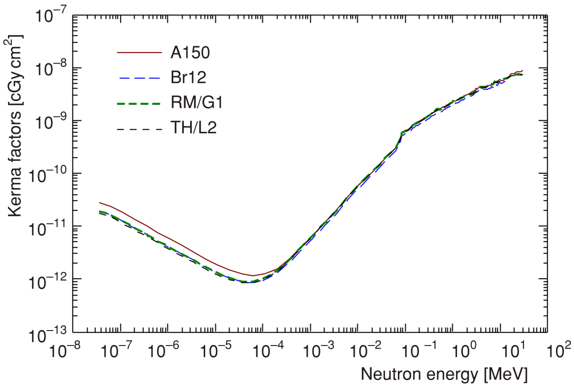

Figure 8. Neutron kerma factors for A150, BR12, RM/G1, and TH/L2

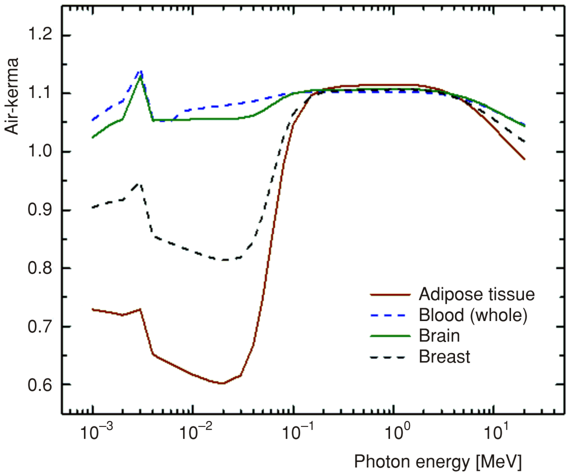

Figure 9. Photon air-kerma for adipose tissue, blood (whole), brain and breast

The ratio of neutron kerma factor of human body and tissue substitutes to water are found to be very large for neutron energies below 100 eV, whereas for neutron energies higher than 100 eV, this ratio becomes unity, except for skeleton cortical bone (SnCb). It can be noted that the ratio for skeleton cortical bone (SnCb) becomes much less than unity compared with other human body and tissue substitutes.

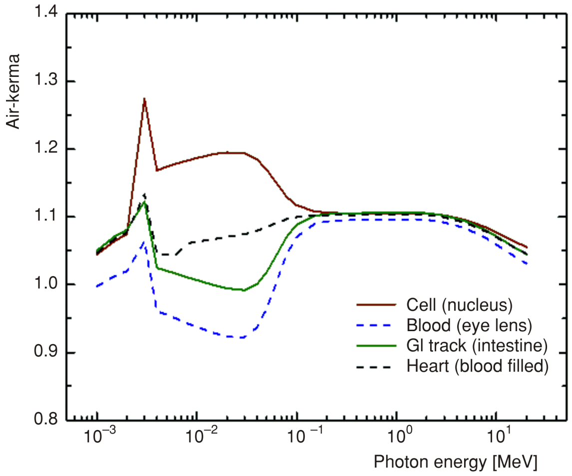

Figure 10. Photon air-kerma for cell nucleus, blood (eye lens), GI track and heart (blood filled)

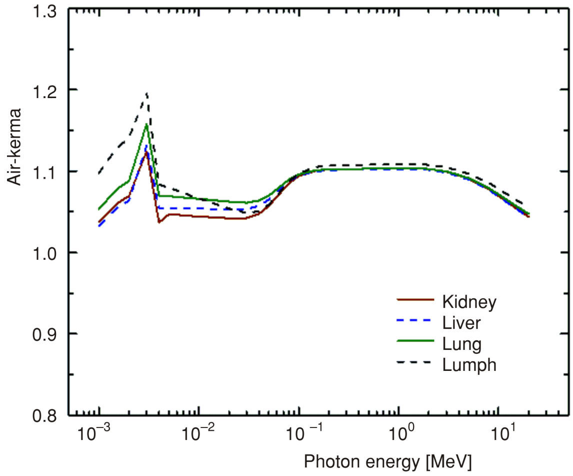

Figure 11. - Photon air-kerma for kidney, liver, lung and lymph

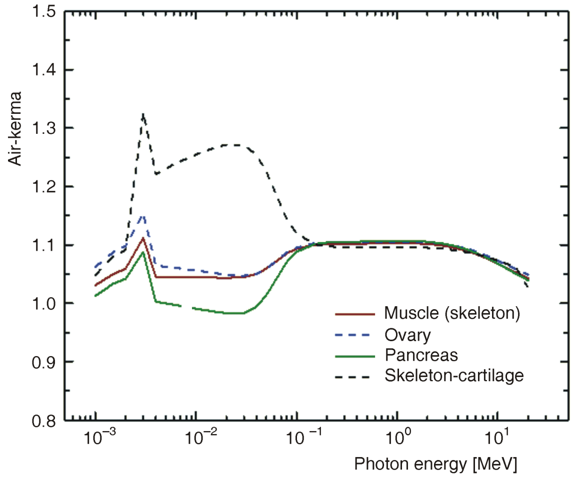

Figure 12. Photon air-kerma for muscle (skeleton), ovary, pancreas and skeleton cartilage

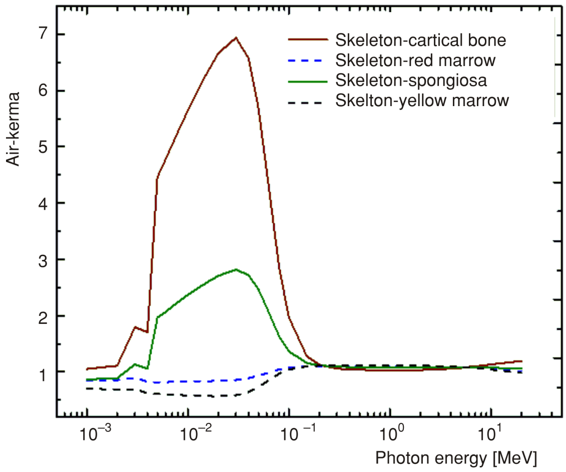

Figure 13. Photon air-kerma for skeleton-red marrow, skeleton-spongonia and skeleton-yellow marrow

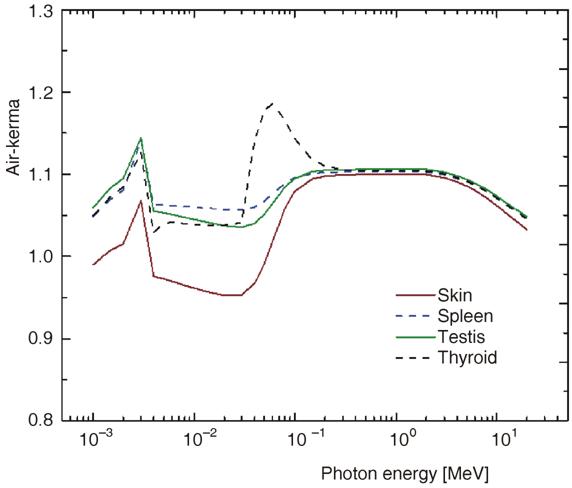

Figure 14. Photon air-kerma for skin, spleen, testis and thyroid

CONCLUSIONS

The photon air-kerma and neutron kerma factors for human organs and tissue substitutes were investigated. The photon air-kerma for human body organs and water were found to be near unity for energies above 100 keV. The ratio of the mass-energy absorption coefficients of human organs to water, showed large deviation from unit for energies below 100 keV, while the ratio of the neutron kerma factor for human organs to water, showed deviation from unit for energies below 100 eV. The neutron kerma factors of human organs and water are found to be the same order of magnitude while there are significant differences in comparison in to air kerma factors.

For neutrons with energies 63 eV up to 200 keV the neutron kerma factors of human organs and tissue substitutes were found to be equal to water. However, for neutron energies between 63 eV to 200 keV the obtained data for skeleton-cortical bone (SnCb) were

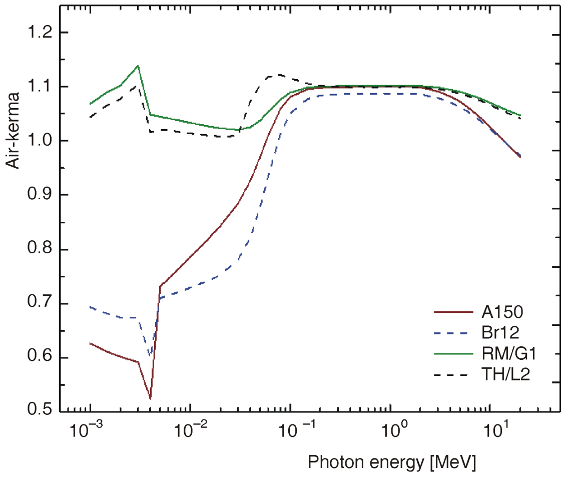

Figure 15. Photon air-kerma for A150, BR12, RM/G1 and TH/L2

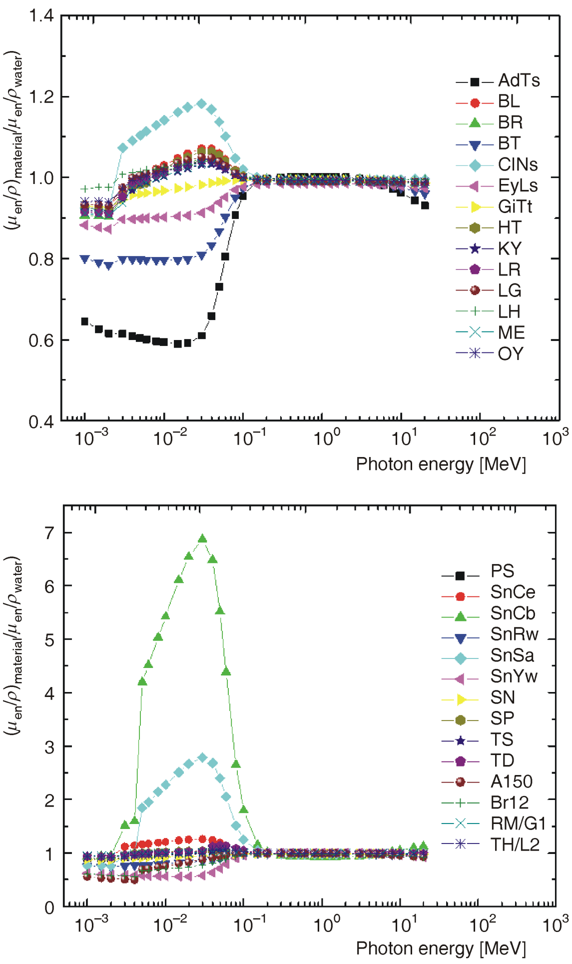

Figure 16. Ratio of mass-energy absorption coefficients of human organ and tissue substitutes to water

found to be away from water equivalence for low-energy photons and high-energy neutrons.

AUTHOR'S CONTRIBUTION

The idea for investigation of the neutron and photon kerma parameters for human body organs was put forward by V. P. Singh for various medical applications, the calculations were done by V. P. Singh and H. R. Vega-Carrillo, and analysis and discussion was carried out by V. P. Singh, N. M. Badiger, and H. R. Vega-Carrillo. The manuscript and figures were prepared by V. P. Singh and H. R. Vega-Carrillo.

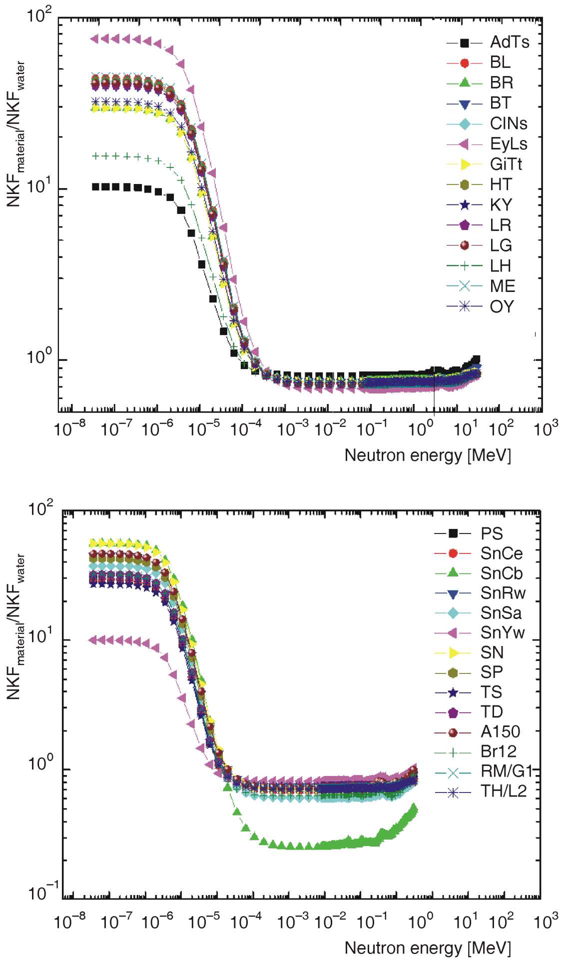

Figure 17. Ratio of neutron kerma factor of human organ and tissue substituessubstitutes to water

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