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Neutron kerma factors and water equivalence of some tissue substitutes

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HIGHLIGHTS

- We calculated the neutron kerma factors of tissue substitutes up to 29 MeV.
- Water equivalence was observed above neutron energy 100 eV.
- Natural rubber was found to be a water equivalent material.
- Kerma factors are in agreement with those published in literatures.

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ABSTRACT

The Kerma factors and Kerma relative to the air and water of 24 compounds that are used as tissue substitutes were calculated for neutron energies ranging from 2.53×10^{-8} to 29 MeV. The Kerma ratios of the tissue substitutes relative to air and water were calculated. The water equivalence of the selected tissue substitutes was observed above neutron energies of 100 eV. The Kerma ratio relative to the air for poly-vinylidene fluoride and Teflon were nearest to unity at very low energy (up to 1 eV) and above 63 eV, respectively. It was found that the natural rubber was a water-equivalent tissue substitute compound. The results of the Kerma factors in our investigation show good agreement with those published in ICRU-44. We found that at higher neutron energies, the Kerma factors and Kerma ratios of the selected tissue substitute compounds were approximately the same, but though the differences were large for energies below 100 eV.

1. Introduction

Kinetic energy released per unit mass (Kerma) is defined as the initial kinetic energy of all secondary charged particles liberated per unit mass at a point of interest by uncharged radiation (ICRU 1989; Attix, 1986). It is applicable to all photons and neutrons that have the same unit as the absorbed dose. In the case of photon radiation, the energy fluence, Ψ is related to Kerma through mass energy transfer coefficients μ_{tr}/ρ, thus $K = \psi\frac{\mu_{tr}}{\rho}$. In neutron radiation, the particle fluence ϕ is the relevant quantity, so the analogous definition is $K = \phi k_f$, where k_f is called the "Kerma factor". The Kerma factor is related to the mass energy transfer coefficient (for mono-energetic neutrons of energy E_n) as $k_f = E_n\frac{\mu_{tr}}{\rho}$ (Caswell et al., 1982).

Neutron-induced reactions play an important role in particle transport, radiation effects for transmutation, and medical and material research. Neutron interaction is high linear energy transfer (LET) which interacts primarily via (n, p) or spallation reactions, thereby depositing a large amount of energy and often transforming the atom in the DNA strand into a completely different atom.

A tumor cell whose DNA is damaged to this extent cannot repair itself and will ultimately die. However, under low LET radiation (x- and γ-rays), the outer electrons of the atoms in the tumor cells are displaced, which temporarily ionizes the atoms, but also allows time for the electrons to return to orbit and rebuild the tumor's DNA through chemical reactions. These reactions are completed through the activated radicals that are produced during the atomic interactions. This rebuilding process allows for the growth of the tumor. Therefore, neutron therapy is superior for cancer treatment compared with photon and proton therapy

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because of its higher biological effectiveness, exponential cell survival and slow DNA damage. The sensitivity of salivary gland tumors, sarcomas, and melanomas and prostate tumors is higher than that obtained with photon exposure.

The cancer cells damaged by high LET radiation have a low probability to repair and continue to grow compared with damage by low LET radiation. This inability for the tumor to repair is one parameter that accounts for the higher relative biological effectiveness of neutron therapy. The relevance of radiation therapy with photons, electrons, and neutrons has been discussed in reports published by the International Commission on Radiation Units and Measurements (ICRU, 1989).

The dose of neutrons required to kill the same number of cancerous cells is approximately one third of the dose of photons (Chadwick et al., 1997). Clinical reports indicate that treatment with neutrons consists of less exposure compared with treatment with photons or electrons. Practical neutron/photon treatment of a tumor involves the exposure of some healthy tissues to sub-lethal doses.

Radiation treatment for a patient requires extensive work and a database for the energy deposition of the radiation in human organs and tissues. The energy deposition of radiation into the human organs can be studied by using phantoms and simulation methods. The phantom materials are chosen to have equivalent properties against radiation (X, γ and neutron) interactions. The neutron energy deposition and the energy of the generated charged particles are important in fast neutron therapy (Kononov et al., 2006).

Kerma factors for neutrons in low-Z materials or compounds are important for the dosimetry of neutron radiotherapy beams (Wuu and Milavickas, 1987). When determining the Kerma factors for neutrons in the different compounds that are used in radiotherapy, the elemental composition is important because it is primarily determined by the hydrogen content of tissues. The neutron–proton elastic scattering processes dominate the energy transfer process, even at neutron energies of 60–70 MeV (Maughan et al., 1997). The neutron interactions in various types of compounds, mixtures and elements have been investigated (MousaviShirazi and Sardari, 2013; Adnan 2010; Sheino et al., 2004; Xiaojun et al., 2011; Zhenzhou and Jinxiang, 2008; Meulders et al., 2000; Schrewe et al., 2000).

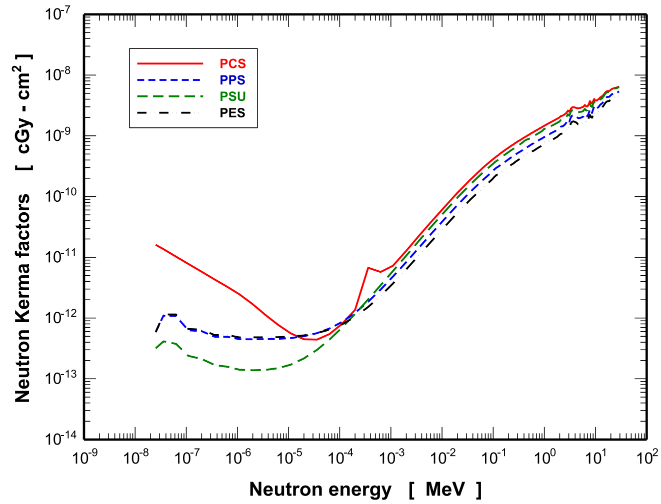

Fig. 1. Neutron kerma factors of PCS, PPS, PSU and PES.

Kerma values of gamma radiation are used in dosimetry for dose evaluation. Similarly during the neutron interaction in the medium, the Kerma values are defined for medical applications. The use of the Kerma factor in neutron Dosimetry has been reviewed in the literature (ICRU, 2000, Kondo et al., 2008; Sun et al., 2008). The neutron Kerma factors of human organs and few tissue substitutes have been reported (ICRU, 1989). Also, photon Kerma factors of alcohols and thermoluminescent dosimeters have been reported (Singh and Badiger 2013a, 2013b).

The aim of this work was to calculate the neutron Kerma factors (Kerma per unit neutron fluence) of some tissue substitute compounds. These Kerma factors were used to calculate the values relative to air and water. The water equivalence was calculated because water exhibits the most useful dosimetric properties for medical applications. The present study is useful for neutron applications in medical and simulation work that use the tissue substitute compounds.

Table 1
Elemental composition of tissue substitutes.

ID	Tissue substitutes	ρ [g/cm^3]	Weight fraction [%]								
			H	C	N	O	F	S	Cl	Ca	Na
PCS	Poly-chloro-styrene	1.55	6.19	69.63	0.00	0.00	0.00	0.00	24.18	0.00	0.00
PPS	Poly-phenylene sulfide	1.64	3.73	66.63	0.00	0.00	0.00	29.65	0.00	0.00	0.00
PSU	Poly-sulfone	1.25	5.01	73.28	0.00	14.46	0.00	7.25	0.00	0.00	0.00
PES	Poly-ether-sulfone	1.37	2.72	48.63	0.00	16.19	0.00	32.46	0.00	0.00	0.00
MC	Modeling clay	1.27	0.00	19.76	0.86	75.83	0.00	3.55	0.00	0.00	0.00
NR	Natural rubber	0.92	11.84	88.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PP	Poly-propylene	0.95	14.37	85.63	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PSc	Plastic-scintillator	1.06	8.53	91.47	0.00	0.00	0.00	0.00	0.00	0.00	0.00
PX	Perspex	1.18	8.05	59.98	0.00	31.96	0.00	0.00	0.00	0.00	0.00
BK	Bakelite	1.36	5.74	77.46	0.00	16.80	0.00	0.00	0.00	0.00	0.00
PAN	Poly-acrylo-nitrile	1.15	5.70	67.90	26.40	0.00	0.00	0.00	0.00	0.00	0.00
TF	Teflon	2.20	0.00	24.02	0.00	0.00	75.98	0.00	0.00	0.00	0.00
PVDF	Poly-vinylidene fluoride	1.78	3.15	37.51	0.00	0.00	59.34	0.00	0.00	0.00	0.00
OAW	Orange articulation wax	0.93	2.72	82.00	7.37	7.82	0.00	0.08	0.00	0.00	0.00
PETE	Polyethylene terephthalate	1.38	4.20	62.50	0.00	33.30	0.00	0.00	0.00	0.00	0.00
BW	Bee wax	0.96	1.87	75.25	8.42	14.27	0.00	0.19	0.00	0.00	0.00
RAW	Red articulation wax	0.91	0.36	80.17	11.23	8.14	0.00	0.09	0.00	0.00	0.00
PF1	Paraffin 1	0.96	0.61	81.73	0.74	16.81	0.00	0.10	0.00	0.00	0.00
PF2	Paraffin 2	0.92	0.68	79.61	9.63	9.94	0.00	0.14	0.00	0.00	0.00
BL	Bolus	1.11	0.50	82.22	0.78	16.41	0.00	0.09	0.00	0.00	0.00
PT	Pitch	1.15	0.19	42.18	0.42	56.76	0.00	0.46	0.00	0.00	0.00
PMMA	Methylmetacrylate	1.18	0.24	94.96	4.71	0.00	0.00	0.10	0.00	0.00	0.00
——	Solid water	1.02	8.10	67.20	2.40	19.90	0.00	0.00	0.10	2.30	0.00
——	Frigerio gel	1.12	10.00	12.00	4.00	73.30	0.00	0.20	0.10	0.00	0.40