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Radiation Dose Coefficients for Healthcare Waste and Water Comparison

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Abstract: According to national and international standards, some groups and subgroups of Healthcare Services Waste (RSS) must undergo some type of treatment to reduce or eliminate the pathogen load before final disposal, to avoid harm to human health and the environment. The pathogens present in the infecting HCW can be effectively inactivated by radiation, providing a uniform minimum dose recommended over the entire volume of the HCW. The analysis of radiation transport in HCW containment containers require determination of the radiation dose coefficients, called: KERMA-fluence for photons and the Mass Stopping Power for electrons; to verify whether the absorbed dose in the container was sufficient for pathogenic inactivation. The chemical compositions of segregated HCW, as well as non-segregated HCW, were evaluated by previous analytical studies by means of segregation of hospital waste. The mass energy absorption coefficients for the chemical composition of HCW at various energies of photon beams and the related density of the RSS supported the calculations of the Radiation Dose Coefficients, KERMA-fluence, and the Mass Stopping Power of electrons for HCW. The results for HCW were compared with equivalent water parameters. The water material does not represent a good substitute for HCW in the dosimetric processes of calibration of exposures to X-ray radiation and electrons in most of the energy spectrum analyzed. There are significant differences between the KERMA-fluence and Mass Stopping Power coefficients of the HCW in relation to water, inducing a very different energy fluency in the RSS in relation to water. A better radiological characterization of HCW for the purpose of sterilization by ionizing radiation was achieved. The Radiation Dose coefficients in the analyzed energy fluence range proved to be useful in the predictions of absorbed dose at exposures of non-standard volumes of RSS.

Keywords: KERMA-fluence coefficient, Mass Stopping Power, Composition of Hospital Healthcare Waste, Pathogenic Radiation Inactivation, Industrial Irradiation.

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Coeficientes de Dose de Radiação para Resíduos de Serviço de Saúde e Comparação com a Água

Resumo: De acordo com os padrões nacionais e internacionais, alguns grupos e subgrupos de Resíduos de Serviços de Saúde (RSS) devem passar por algum tipo de tratamento para reduzir ou eliminar a carga patogênica antes da disposição final, a fim de evitar danos à saúde humana e ao meio ambiente. Os patógenos presentes nos RSS infectantes podem ser efetivamente inativados por radiação, fornecendo uma dose mínima uniforme preconizada em todo o volume dos RSS. A análise do transporte de radiação em recipientes de contenção de RSS requer a determinação dos coeficientes de de dose de radiação, chamados: KERMA-fluência para fótons e o Poder de Freamento de Massa para elétrons; para verificar se a dose absorvida no embalado foi suficiente para a inativação patogênica. As composições químicas dos RSS segregados, assim como dos não segregados, foram avaliadas por estudos analíticos anteriores por meio de segregação de resíduos hospitalares. Os coeficientes de absorção de energia mássica para a composição química dos RSS em várias energias de feixes de fótons e a densidade relacionada dos RSS apoiaram os cálculos dos Coeficientes de de Dose de radiação, KERMA-fluência e o Poder de Freamento de Massa de elétrons para RSS. Os resultados para RSS foram comparados com parâmetros equivalentes da água. O material água não representou um bom substituto para os RSS nos processos dosimétricos de calibração das exposições à radiação de raios X e elétrons na maior parte do espectro de energia analisado. Há diferenças significativas entre os coeficientes de KERMA-fluência e de Poder de Freamento de Massa dos RSS em relação à água, induzindo uma fluência de energia bastante diferente nos RSS em relação à água padrão. Uma melhor caracterização radiológica dos RSS para fins de esterilização por radiação ionizante foi alcançada. Os coeficientes de Dose de Radiação na faixa de fluência de energia analisada se mostraram úteis nas previsões de dose absorvida em exposições de volumes não padronizados de RSS

Palavras-chave: Coeficiente KERMA-fluência, Poder de Freamento de Massa, Composição dos Resíduos de Serviços de Saúde, Inativação Patogênica por Radiação, Irradiação Industrial.

1. INTRODUCTION

Preclinical sterilization of medical products — such as gloves, gauze, syringes, and catheters — involves exposure to radiation beams in industrial irradiators. Radiation processes employing high-power electron accelerators are attractive due to their high energy efficiency, resulting in competitive per-unit costs compared to conventional chemical methods. Additionally, photon beam processing consumes less energy than typical heat-based incineration, eliminates the need for stringent temperature or humidity control, and enables the immediate use of irradiated materials.

The application of this technology in the sterilization of Health Care Waste (HCW) requires demonstrations of both technical and economic feasibility. The feasibility of radiation treatment of HCW is assessed by its ability to inactivate pathogens in packaged waste, which depends directly on the homogeneity and magnitude of the absorbed dose. A practical method for demonstrating efficacy involves computer simulation of radiation transport in HCW packages, allowing evaluation of fluence and spatial dose distribution relative to the thresholds required for pathogen inactivation.

Accurate characterization of packaging is essential for effective HCW sterilization; however, determining the composition of HCW is challenging due to the varying medical product usage across hospital sectors and differences in local economic conditions.

Characterizing HCW is a complex task that involves risks inherent to the process of opening and segregating packages, as it entails handling infectious material. To overcome this challenge, the characterization analyses selected hospitals with similar sectors and procedures, performing segregation and quantitative/statistical analyses to obtain comparable characterization. Subsequently, the average generation of HCW in kg/bed-day is determined, an important indicator for hospital waste management.

The objective of this research was to determine the Radiation Dose Coefficients KERMA-fluence and Mass Stopping Power Coefficients of the HCW for various photons and electron energy beams, through the analysis of the chemical composition and density of the components present in HCW, and to compare these coefficients with those of water. This analysis aimed to dosimetrically characterize HCW in order to evaluate the feasibility of using water as a component of simulant materials in the dosimetric process of HCW irradiation.

2. MATERIALS AND METHODS

2.1. Segregation of HCW

The Segregation of HCW was based on the Resolution of the Brazilian Health Regulatory Agency (Anvisa) RDC nº 306 [3], which was later replaced by Resolution of the Brazilian Health Regulatory Agency (Anvisa) RDC nº 222 [4], with the classification being maintained. HCW was classified into Group A and its subgroups, B, D, and E; this classification was based on data collected from six hospitals in Vitória/ES, Brazil, through analysis of the content of open containment containers by ADUAN *et. al* [5]. As per this same source, it was observed that none of the hospitals segregated Group A HCW into ~~all~~ its subgroups (A1, A2, A3, A4, and A5), a trend that continues nationwide.

HCW was identified as belonging to Group A – infectious, across various groups and subgroups. Following the literature, approximately 57 % of HCW was categorized in Group D – common, 41 % in Group A – biological risk, 1.5 % in Group B – chemical risk, and 0.05% in Group E – sharp. Group A is comprised entirely of HCW from subgroups A1 and A4, as waste types A2, A3, and A5 are easily distinguishable and have well-defined legislation and protocols, typically not mixed with subgroups A1 and A4. The proportion of Group E waste in the mixture was considered very small and therefore not relevant for characterization purposes.

The methodology employed to determine the stoichiometric chemical elements of Healthcare Waste (HCW) was based on Resolution of the Brazilian Health Regulatory Agency (Anvisa) RDC No. 751 [6], which mandates that every medical product manufacturer must provide a Brazilian Health Regulatory Agency Technical Dossier [7]. Among various technical product information, this dossier must describe its chemical composition, indicating characteristics, purpose, mode of use, content, special precautions, potential risks, production process, and additional necessary information.

The chemical composition of segregated products was assessed using the HCW segregation data conducted by ADUAN *et. al* [5]., through the mandatory Brazilian Health Regulatory Agency Technical Dossier [7]. The relative proportion of each material present in the waste was determined using segregation into groups A (A1 and A4), B, and D.

2.2. Determining the Mass Ratio of each element of HCW

The composition and proportion of each distinct product existing in HCW was determined by ADUAN *et. al* [5] through the mechanical separation of this type of waste in 6 different hospitals in Brazil. The Anvisa's Technical Dossier was consulted, in which each manufacturer must mandatorily inform the chemical composition of its product for commercialization. Thus, the constituent products of HCW can be recovered and we were able to determine the stoichiometric proportions of each element in HCW by the chemical composition of the separated products and the proportion of these products in HCW.

The proportion of each element in a chemical substance is given by the ratio of the total mass of one element in one substance to the molar mass of this substance. The chemical representation of a health product present in the HCW is given by $X_nY_mZ_p$ where X, Y, Z are the chemical elements in the formula, the subscripts n, m, p are the quantity of each chemical element in the formula. The proportion δ of a certain element X, Y, Z in the formula (1) is given by:

$$\delta = \alpha/\beta \quad , \tag{1}$$

where α= (n.A_X; m.A_Y…); β=(n.A_X + m.A_Y + pA_Z+⋯) and A corresponds to the molar mass of a given element. To determine the proportion of the other elements in the formula, simply replace the numerator with the product of the number of atoms of the element in the formula by the molar number of that element.

2.3. Coefficient Kerma and Stopping Power evaluation

The KERMA-fluence coefficient C_k for a HCW and water material is evaluated by:

$$C_k(E_\gamma) = K/\Psi = E_\gamma \sum_{k=0}^{n} (\mu_{tr}/\rho) \quad , \tag{2}$$

in which Ψ is the fluency of gamma rays, E_γ is the energy of the gamma ray, μ_{tr} is the mass energy transfer coefficient for gamma rays. The sum represents the incremental contribution of individual chemical elemental composition present in the material. The data of the Mass Energy Attenuation Coefficient was available by NIST [10]. The unit in equation (2) is given by Gy cm^2. The C_k was determined for both HCW and water at X-ray beams with energies ranging from 0.001 MeV to 20 MeV.

The stopping power (S) quantifies the average energy loss per pathlength of charged particles in the matter. In principle, the stopping power consists of three contributions, namely the electronic (or collision), the radiative, and the nuclear stopping power. The nuclear stopping power is negligible for electrons; however, it can be significant for heavy ions, given by ICRU 44 [9].

The mass radiative stopping power of compounds and mixtures is evaluated according to Bragg's additivity rule [11].

The Bragg additivity rule is a useful concept in the study of mass stopping power. It allows us to approximate the mass stopping power of a substance compound medium by considering the weighted sum of the stopping powers of its elemental constituents.

Material composed of different elements like HCW, the Total Mass Stopping Power $\frac{1}{\rho}S^{-}{}_{t}(T)$ can be estimated by adding up the contributions from each individual element.

$$\frac{1}{\rho}S^{-}{}_{t}(T) = \sum_i \xi_i \left[\frac{1}{\rho}S_{el}{}^{-}(T)\right]_i + \sum_i \xi_i \left[\frac{1}{\rho}S_{rad}{}^{-}(T)\right]_i \tag{3}$$

in which ξ_i , $\left[\frac{1}{\rho}S_{el}{}^{-}(T)\right]_i$ and $\left[\frac{1}{\rho}S_{rad}{}^{-}(T)\right]_i$ are the fraction by weight of the electronic and radiative mass stopping power of the i^{th} atomic constituent respectively.

The free ESTAR program provided by NIST [12] calculates the Mass Stopping Power, density effect parameters, range, and radiation yield for electrons in various elements or mixtures of materials by simply entering the density and chemical composition of a substance. For HCW, the mass density was 0.15 g.cm^{-3} provided by NEVES [13] and the water density taken 1.0 g.cm^{-3}. The Mass Stopping Power information is specified as a function of power in the range of 0.001 MeV to 100.00 MeV. Similar, the total mass stopping power, S/ρ for charged particles was evaluated by the sum of the contribution of each chemical elemental composition in the material. Additional information is available in literature [9-12].

3. RESULTS AND DISCUSSIONS

Tables 1, 2, 3 and 4 present the material components of HCW separated by groups and subgroups A1, A4, B and D, where tA (A1+A4), tB, tD correspond to the total mixture of chemical substances in their respective group.

Table 1 : Stoichiometric composition of HCW Group A1 by component.

A1	Components	Main Substance and Chemical Formula	SP (%)	PS (%)	A1 / tA (%)
A1-1	Leftover laboratory specimens containing blood or body fluids.	Polyethylene Terephthalate $(C_{10}H_8O_4)n$	$(C_{10}H_8O_4)n$ C - 62.50, H - 4.20, O - 33.30	96	11.32

A1	Components	Main Substance and Chemical Formula	SP (%)	PS (%)	A1 / tA (%)
A1-2	Transfusion bags, containing blood or blood components.	Polyvinyl chloride – PVC $(CH_2\text{-}CHCl)n$	$(CH_2\text{-}CHCl)n$ C – 38.44, H – 0.05, Cl – 56.71	100	1.10
A1-3	Vaccines with live or attenuated microorganisms.	Booxylicate (SiO_2) $+(B_2O_3)$ $+(Na_2O)$ $+(Al_2O_3)$	(SiO_2) Si – 46.74, O – 53.26 + (B_2O_3) B – 31.06, O – 68.94 + (Na_2O) Na– 74.19, O – 25.81 + (Al_2O_3) Al – 52.93, O – 47.07	81 + 13 + 4 + 2	0.99
A1-4	Culture Media	Agar – Agar Hydrated + nutrients H_2O	H_2O: H –11.19, O – 88.81	98	0.87
A1-5	Cultures and stocks of microorganisms, instruments for transfer, inoculation or mixtures of cultures.	High-impact polystyrene + Hydrated Culture Medium $(C_8H_8)n+ H_2O$	$(C_8H_8)n$: C – 92.3, H – 7.7 + H_2O : H – 11.19, O – 88.81	90 + 10	0.17

PS- Proportion of the main substance in the component; SP - Stoichiometric proportion of each element in the formula; Source : Produced by the Authors

Table 2 : Stoichiometric composition of HCW Group A4 by component.

A4	Componentes	Main Substance and Chemical Formula	SP (%)	PS (%)	A4 / tA (%)
A4-1	Gauze, cotton, bandage	Cellulose $C_6H_{10}O_5$	$C_6H_{10}O_5$: C – 44.45, H – 6.21, O – 49.34	99	22.82
A4-2	Latex Gloves	Methyl -1,3-Butadiene 1,3 C_5H_8	C_5H_8 : C – 88.16, H – 11.84	99	22.24
A4-3	HCW Packing Plastic Bags	Low-density polyethylene (LDP) $(C_2H_4)n$	$(C_2H_4)n$: C – 85.63, H – 14.37	100	12.37
A4-4	Disposable Personal Protective Equipment Parts (Hoods, hats, masks)	High Density Polypropylene (HDP) $(C_3H_6)n$	$(C_3H_6)n$: C – 85.63, H – 14.37	95	10.57
A4-5	Disposable syringes without needle	High Density Polypropylene (Syringe Body) $(C_3H_6)n$ + Polybutadiene (Plunger Rubber $(C_4H_6)n$	$(C_3H_6)n$ C – 85.63, H – 14.37 + $(C_4H_6)n$ C – 88.82, H – 11.19	95+5	3.60
A4-6	Arterial line kits, intravenous lines, dialyzers	Polyvinyl chloride (PVC) $(CH_2\text{-}CHCl)n$ + Celulose acetato	$(CH_2\text{-}CHCl)n$: C –38.44, H – 4.85, Cl – 56.71	20 +57 +20	8.30

A4	Componentes	Main Substance and Chemical Formula	SP (%)	PS (%)	A4 / tA (%)
		$CH_3COOCH_2CH_3$ + Polycarbonate $(C_{16}H_{14}O_3)n$	$+CH_3COOCH_2CH_3$: C – 54.53, H – 9.15 , O – 36.32 + $(C_{16}H_{14}O_3)n$: C –75.58, H – 5.54 , O – 18.88		
A4-7	Leftover laboratory samples and their containers, containing feces, urine, and secretions	Water H2O + Solid material based on carbon, potassium and calcium C + K + Ca + High Density Polypropylene (HDP) $(C_3H_6)n$	H_2O H – 11.18 , O – 88.82 + (C + K + Ca) C – 80.0, K – 8.0, Ca – 12.0 + $(C_3H_6)n$ C – 85.6, H – 14.4	65 +25 +5	2.09
A4-8	Urine collection system (closed system)	Policloreto de Vinila - PVC $(CH_2\text{-}CHCl)n$	$(CH_2\text{-}CHCl)n$ C – 38.44, H – 4.84, Cl – 56.73	100	1.39
A4-9	Empty transfusion bags or those with post-transfusion residual volume	Polyvinyl chloride (PVC) $(CH_2\text{-}CHCl)n$	$(CH_2\text{-}CHCl)n$ C – 38.44, H – 4.84, Cl – 56.73	100	0.41
A4-10	Urine collection system (open), uripen	Isoprene $(C_5H_8)n$	$(C_5H_8)n$ C – 88.16, H – 11.84	100	0.46
A4-11	Test tube caps	High Density Polypropylene (HDP) $(C_3H_6)n$	$(C_3H_6)n$ C – 85.63 %, H – 14.37	100	0.23
A4-12	Nasogastric catheter	Polyvinyl chloride (PVC) $(CH_2\text{-}CHCl)n$	$(CH_2\text{-}CHCl)n$ C – 38.44, H – 4.84, Cl – 56.73	100	0.23
A4-13	Humidifier with plastic trachea	High Density Polypropylene (HDP) $(C_3H_6)n$	$(C_3H_6)n$ C – 85.63, H – 14.37	100	0.23
A4-14	Closed system drain	Polyethylene $(C_2H_4)n$	$(C_2H_4)n$: C – 85.63 %, H – 14.37 %	100	0.29
A4-15	Orotracheal tube	Polyvinyl chloride (PVC) $(CH_2\text{-}CHCl)n$	$(CH_2\text{-}CHCl)n$ C – 38.44 %, H – 4.84 %, Cl – 56.73 %	100	0.12
A4-16	Surgical instruments (catheters and guidewires)	Polytetrafluoroethylene (PTFE) $(C_2F_4)n$ + Stainless steel alloy (Fe (85%) / Cr (15%))	$(C_2F_4)n$ C – 24.02, F - 75.98 + Aço Inox Fe – 85.0, Cr – 15.0	60 +40	0.12
A4-17	Oral cavity aspirator kit	Policloreto de Vinila – PVC $(CH_2\text{-}CHCl)n$	$(CH_2\text{-}CHCl)n$: C – 38.44, H – 4.84, Cl – 56.73	100	0.06

PS - Proportion of the main substance in the component; SP - Stoichiometric proportion of each element in the formula; Source : Produced by the Authors.

Table 3 : Stoichiometric composition of HCW Group B by component.

B	Components	Main Substance and Chemical Formula	SP (%)	PS (%)	B / tB (%)
B-1	Drugs	Binder (starch-hydrated) +Active ingredient $(C_6H_{10}O_5)n$	$(C_6H_{10}O_5)n$ C – 44.44, H – 6.22, O – 49.34	20	1.04
B-2	Packaging containing sanitizing and disinfectant residues	High Density Polyethylene (HDP) $(C_3H_6)n$ +Hydrogen Peroxide H_2O_2	$(C_3H_6)n$:C – 85.63, H – 14.37 + H_2O_2 : H – 6.31, O – 93.69	99 + 1	8.96

PS - Proportion of the main substance in the component; SP - Stoichiometric proportion of each element in the formula; Source : Produced by the Authors

Table 4 : Stoichiometric composition of HCW Group D by component.

D	Components	Main Substance and Chemical Formula	SP (%)	PS (%)	D / tD (%)
D-1	Toilet paper, diaper, sanitary napkins.	Cellulose $(C_{12}H_{20}O_{10})n$ + Sodium Polyacrylate (SPA) $(C_3H_3O_2Na)n$ + Polypropylene $(C_3H_6)n$ + Polyethylene $(C_2H_4)n$ + Polyamide $(C_{12}H_{22}N_2O_2)n$ + Elastane $(C_{32}H_{30}O_7N_6)n$	$(C_{12}H_{20}O_{10})n$: C – 44.44, H – 6.22, O – 49.34 + $(C_3H_3O_2Na)n$: C – 38.30, H – 3.22, O – 34.04, Na – 24.45 + $(C_3H_6)n$: C – 85.63, H – 14.37 + $(C_2H_4)n$: C – 85.63, H – 14.37 + $(C_{12}H_{22}N_2O_2)n$: C – 63.67, H – 9.80, O – 12.38, N – 14.14 +$(C_{32}H_{30}O_7N_6)n$: C – 62.89, H – 4.95, O – 18.34, N – 13.76	46 + 28 + 10 + 13 + 2 + 1	35.40
D-2	Serum and similar equipment	Polyvinyl chloride (PVC) $(CH_2\text{-}CHCl)n$	$(CH_2\text{-}CHCl)n$ C – 38.44, H – 4.84, Cl –56.73	99	27.23
D-3	Administrative area waste	Cellulose $(C_{12}H_{20}O_{10})n$	$(C_{12}H_{20}O_{10})n$: C– 44.44, H – 6.22, O – 49.34	99	24.09
D-4	Food waste	Carbohydrates (starch) $(C_6H_{10}O_5)n$ + Water H2O	$(C_6H_{10}O_5)n$ C– 44.44, H– 6.22, O – 49.34 + H_2O: H –11.19, O – 88.81	75 + 15	9.34
D-5	Gypsum residues	Calcium Sulfate Dihydrate CaO_4S * 2 H_2O	Ca –23.27, O – 55.76, S – 18.62, H – 2.34	100	3.77
D-6	Wooden spatula	Cellulose $C_{12}H_{20}O_{10})n$ + Hemiceluloses $(C_6H_{10}O_5)n$ + Lignine: $(C_9H_{10}O_2)n$	$(C_{12}H_{20}O_{10})n$: C– 44.44, H – 6.22, O– 49.34 + $(C_6H_{10}O_5)n$: C– 44.44, H – 6.22, O– 49.34 + $(C_9H_{10}O_2)n$: C–71.98, H– 6.71, O– 21.31	50 + 30 + 15	0.04
D-7	Ambu Mechanical Ventilation Mask	Polysulfone of Aryl $C_6H_4\text{-}SO_2\text{-}C_6H_4$	$C_6H_4\text{-}SO_2\text{-}C_6H_4$: C– 66.65, H – 4.73, O – 14.80, S - 14.32	60 +	0.04

D	Components	Main Substance and Chemical Formula	SP (%)	PS (%)	D / tD (%)
		+ Polydimethylsyloxano (Silicone) $(CH_3)_2Si(Cl)_2$	+ $(CH_3)_2Si(Cl)_2$:C– 18.61, H– 4.69, Cl –21.76, Si–54.94	40	
D-8	Transcutaneous pacemaker	Polyvinyl chloride (PVC) $(CH_2\text{-}CHCl)n$ + Carbomer $(CH_2\text{-}CH(COOH))n$ + Water H_2O + High Density Polyethylene (HDP) $(C_3H_6)n$ + Copper cabling Cu	$(CH_2\text{-}CHCl)n$: C – 38.44, H – 4.85, Cl – 56.7 + $(CH_2\text{-}H(COOH))n$: C – 50.01, H – 5.59, O – 44.40 + H_2O: H –11.19, O – 88.81 + $(C_3H_6)n$: C – 85.63, H –14.37, + C u- 100	50 + 15 + 20 + 10 + 5	0.04
D-9	Electrical coagulation system (cardiac ablation)	Polytetrafluoroethylene $(C_2F_4)n$ + Nitinol Alloy $Ni_{14}Ti_{11}$	$(C_2F_4)n$: C– 24.02, F– 75.98 + $Ni_{14}Ti_{11}$: Ni–60.95, Ti – 39.05	80 + 10	0.04

PS - Proportion of the main substance in the component; SP - Stoichiometric proportion of each element in the formula; Source : Produced by the Authors.

The proportions of segregated and non-segregated groups and subgroups within the total HCW mixture were analyzed to determine the distribution of chemical elemental composition across the various HCW groups and subgroups. The following percentage was achieved: A1, 5.96%; A4, 35.27%; B, 1.61%; D, 57.16%, totalizing HCW mixture of A1+A4+B+D of 100%.

The stoichiometric chemical proportions of a given element in the HCW group or subgroup were given by multiplying four-factors: the proportion of that element in the chemical substance, the proportion of that substance in the segregated component and the proportion of that component in its group or subgroup, that is, multiplying the values of the last 3 columns of tables 1, 2, 3, 4 by the values of the proportions in the total mixture given by A1+A4+B+D.

The stoichiometric chemical proportion of the elements of subgroups A1, A4, B and D of HCW is presented in Table 5. In addition, the proportion of the elements in the unsegregated mixture on that group or subgroup is present.

Table 6 shows the stoichiometric proportion of all chemical elements found in HCW groups and subgroups.

Table 5 : Stoichiometric chemical proportion of the elements of subgroups

Subgroup	Chemical Element	Elemental Ratio in HCW (%)	Proportion in HCW mixture (A1+A4+B+D) (%)
A1	Carbon – C	51.5	3.069
	Oxygen – O	34.2	2.038
	Chlorine – Cl	4.3	0.256
	Hydrogen – H	4.0	0.238
	Silicon – Si	2.6	0.155
	Boron – B	0.3	0.018
	Sodium – Na	0.2	0.012
	Aluminum – Al	0.1	0.006
	Total Characterized A1	97.0	5.781
	Global uncertainty A1*	2.5	3.0
A4	Carbon – C	70.05	24.707
	Oxygen – O	16.82	5.932
	Hydrogen – H	8.57	3.023
	Chlorine – Cl	2.41	0.850
	Iron – Fe	0.12	0.042
	Fluor – F	0.11	0.039
	Calcium – Ca	0.07	0.025
	Potassium – K	0.05	0.018
	Cromo – Cr	0.03	0.011
	Total characterized A4	98.23	34.65
	Global uncertainty A4*	2.0	3.0
B	Carbon – C	17.40	0.280
	Oxygen – O	9.06	0.146
	Hydrogen – H	2.41	0.039

Subgroup	Chemical Element	Elemental Ratio in HCW (%)	Proportion in HCW mixture (A1+A4+B+D) (%)
	Total characterized B	28.87	0.465
	Global uncertainty B*	2.0	3.0
D	Carbon – C	42.81	24.470
	Oxygen – O	30.15	17.233
	Chlorine – Cl	15.30	8.475
	Hydrogen – H	6.07	3.470
	Sodium – Na	2.42	1.383
	Calcium – Ca	0.88	0.503
	Sulphur – S	0.70	0.400
	Nitrogen – N	0.15	0.086
	Fluor – F	0.024	0.014
	Nickel – Ni	0.002	0.001
	Titanium – Ti	0.002	0.001
	Copper – Cu	0.002	0.001
	Total characterized D	98.51	56.308
	Global uncertainty D*	2.0	3.0

* The stated global uncertainty is based on a standard uncertainty, multiplied by the coverage factor k = 2, for a 95% probability of coverage. Source : Produced by the Authors

Table 6: Stoichiometric chemical proportion of the elements in the Total HCW Mixture (A1+A4+B+D).

Chemical elements	Proportion of the element in the total HCW mixture (A1+A4+B+D) (%)
Carbon – C	52.526
Oxygen – O	25.349
Chlorine – Cl	9.851
Hydrogen – H	6.770
Sodium – Na	1.395
Calcium – Ca	0.528
Sulphur – S	0.400
Silicon – Si	0.155

Chemical elements	Proportion of the element in the total HCW mixture (A1+A4+B+D) (%)
Nitrogen – N	0.086
Fluor – F	0.053
Iron – Fe	0.042
Boron – B	0.018
Potassium – K	0.018
Chromium – Cr	0.011
Aluminum – Al	0.006
Nickel – Ni	0.001
Titanium – Ti	0.001
Copper – Cu	0.001
Total Characterized	97.211
Global uncertainty*	3.0

* The stated global uncertainty is based on a standard uncertainty, multiplied by the coverage factor k = 2, for a 95% probability of coverage ; Source : Produced by the Authors

The lack of HCW segregation is a common reality, therefore, performing a complete stoichiometric analysis of the elemental groups and subgroups within the mixture in containment containers is often not feasible.

Upon analyzing Table 5, it is observed that the main composition elements of HCW in subgroup A1 are carbon and oxygen, corresponding to approximately 85.7 % of the composition of this waste. It is noted that the main composition elements of the HCW in subgroup A4, as well as in subgroup A1, are also carbon and oxygen, corresponding to approximately 86.9 % of the composition of this waste. It is observed that the main known composition elements of Group B are also carbon and oxygen, corresponding to approximately 28.87 % of the composition of this waste. However, approximately 91.04 % of this waste in the mixture of HCW consists of medications in tablet form, determining which medications these tablets belong to and, consequently, determining the active ingredient and its chemical elements is an extremely complex task, resulting in an uncertainty of approximately 71.13 % of the elements contained in this waste. Despite this large uncertainty in the stoichiometric composition of Group B Waste, its proportion in the mixture of HCW is low, approximately 1.61 %, which means that the uncertainty of elements in the total mixture of HCW, due to Group B, is only 1.14%. The two most present elements in the composition of Group D are also carbon and oxygen, together corresponding to approximately 73.0 % of the mass, followed by chlorine, with approximately 15.3 %. The other elements have relatively low proportions within HCW D.

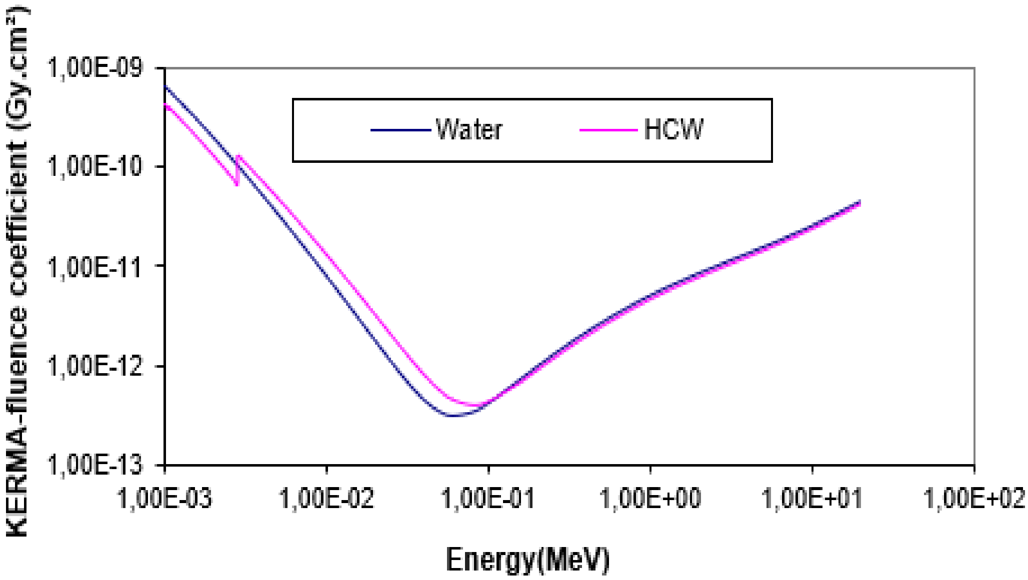
Given the prevalent lack of segregation in healthcare waste (HCW) management in Brazil, excluding a stoichiometric analysis of all elements present in the mixed groups within containment vessels would fail to represent the actual waste conditions. Accordingly, Table 6 provides the stoichiometric chemical composition of the full mixture identified in the HCW containment vessels.

Table 6 reveals that carbon and oxygen are the predominant elements in healthcare waste (HCW), comprising approximately 77.8% of the material's mass within the packaging. Following these, chlorine, hydrogen, and sodium collectively account for about 18.02% of the mass. The remaining elements, each constituting less than 1.00% individually, together make up approximately 1.39% of the total package mass.

The combined uncertainty of the elements in the packaging is approximately 3.00%. This expanded uncertainty is calculated by multiplying the standard uncertainty by a coverage factor (k) of 2, corresponding to a 95% confidence level.

3.1. Determination of X-ray KERMA-fluence Radiation Dose Coefficient from unsegregated HCW and Water

Figure 1 : Comparison between the KERMA-fluence coefficient of Water and HCW.

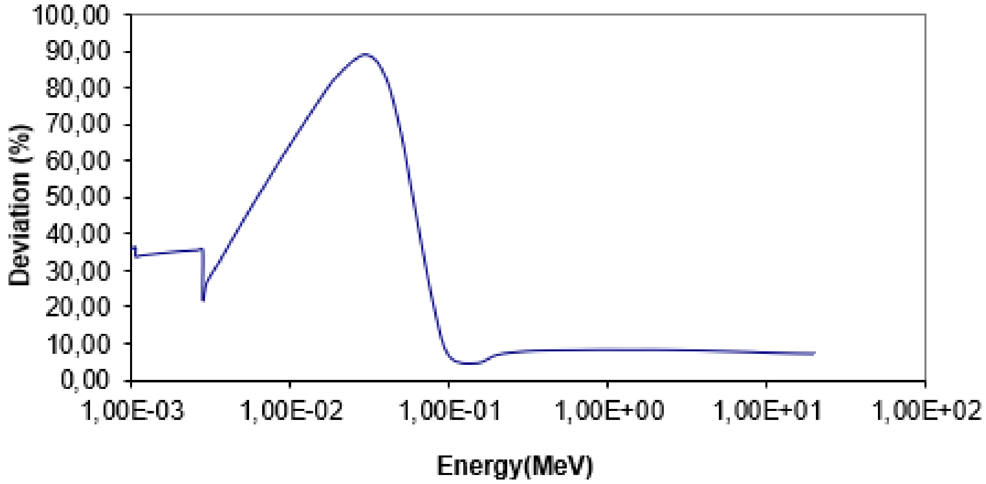


Source : Autor-Print screen from Microsoft Excel 2016 taskbar.

Considering the elements present in significant proportions (greater than 1.0%) in unsegregated healthcare waste (HCW)—namely carbon (C), oxygen (O), chlorine (Cl), hydrogen (H), and sodium (Na) as listed in Table 6—it's noteworthy to compare these with the mass percentages of hydrogen and oxygen in water (H_2O). In water, hydrogen constitutes approximately 11.19% of the mass, while oxygen accounts for about 88.81%.

Figure 1 shows the graphical representation of the KERMA-fluence coefficients for water and HCW. Figure 2 presents the percentage difference between the KERMA-fluence coefficients, both as a function of X-ray beam energy.

Figure 2 : Percentage deviation between Water and HCW Kerma-Fluence.



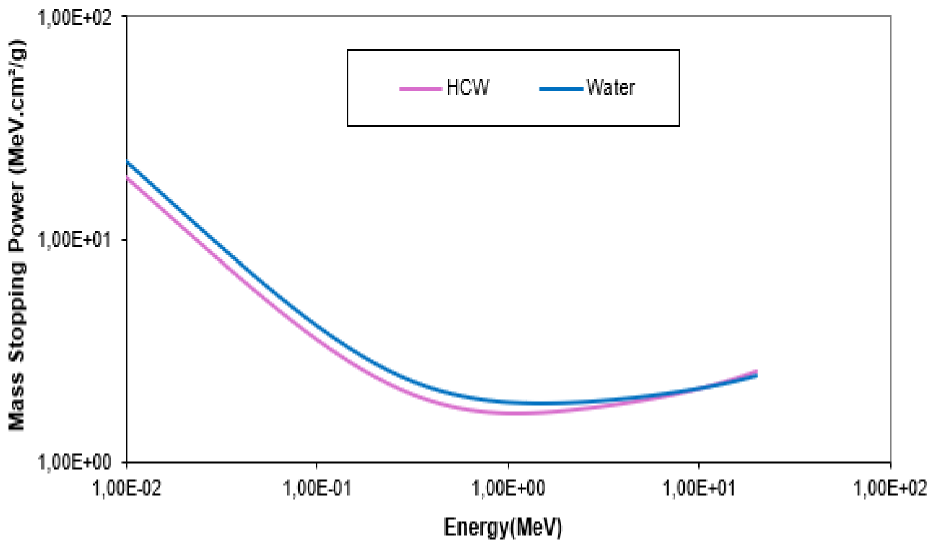
Source : Autor-Print screen from Microsoft Excel 2016 taskbar.

Analyses of Figures 1 and 2, the KERMA-fluence coefficients of both Water and HCW gradually decreases in value up to about 100 keV and then begins not only to increase in value, but the percentage difference between the water and HCW KERMA-fluence coefficient becomes not much less than 10.0 %. At the applications of energies higher than 100 keV would not significantly decrease the relative difference between KERMA-fluence coefficient of Water and HCW but would increase the penetrability of the beam in both materials. Such radiation penetration can be evaluated in particle transport software. This large relative difference between KERMA-fluence coefficients demonstrates that water is not a good substitute for HCW in dosimetric procedures with energy less than 100 keV, and there is a need to develop specific phantoms for calibration of X-ray beams used in the treatment of HCW for pathogenic inactivation with photon beam smaller than this energy.

3.2. Determination of Electron Mass Stopping Power Radiation Dose Coefficient from unsegregated HCW and Water.

Similar to the calculation of KERMA-fluence coefficients, the evaluation of Mass Stopping Power Coefficients for unsegregated healthcare waste (HCW) was based on the elements present in significant proportions (i.e., exceeding 1.0% by mass) namely carbon, oxygen, chlorine, hydrogen, as listed in Table 6. The Mass Stopping Power Coefficients were assessed for both HCW and water under electron beams with energies ranging from 0.001 MeV to 20 MeV.

Figure 3 : Mass Stopping Power coefficients of Water and HCW.

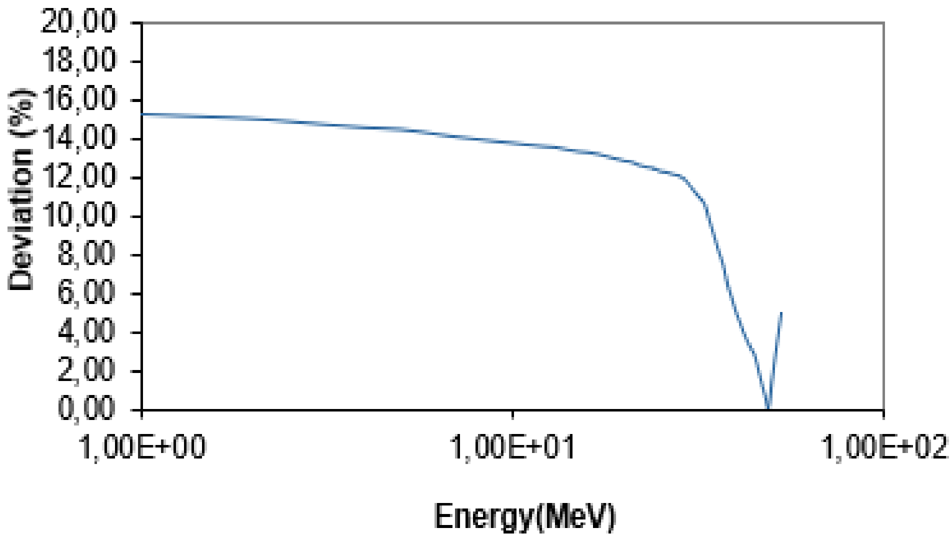


Source : Autor-print screen from Microsoft Excel 2016 taskbar.

Figure 3 depicts the graphical representation of the Water and HCW Mass Stopping Power. In addition, Figure 4 represents the percentage difference between the Mass Stopping Power of water and HCW; both as a function of the energy of the X-ray beams.

Figures 3 showed the Radiation Dose Coefficient Mass Stopping Power of both Water and HCW. The values gradually decrease up to about 1 MeV and then increase (Figure 3). From Figure 4, the percentage difference between the water and HCW Mass Stopping Power coefficient becomes less than 15.0 %, reaching 0% at 20 MeV . Radiation expositions to electron energies between 1 MeV and about 20 MeV would not significantly decrease the relative difference between Mass Stopping Power coefficients of water and HCW but would increase the penetrability of the beam in both materials. The differences in both Radiation Dose Coefficients: Mass Stopping Power and KERMA-fluence coefficients are mainly due to the distinct chemical composition of the materials. Although the Mass Stopping Power is similar to both materials for energy higher than 20 MeV, the monoenergetic incident electron beam slowing down internally in deep, therefore, the deposition of dose in relation to water will be significantly different.

Figure 4 : Percentage deviations between Water and HCW Mass Stopping Power coefficients.



Source : Autor-print screen from Microsoft Excel 2016 taskbar.

4. CONCLUSIONS

After gathering information on the segregation of healthcare waste (HCW) into its groups and subgroups, the stoichiometric chemical composition of the HCW components in subgroups A1, A4, B, and D was determined. Additionally, the stoichiometric proportions of the elements in the total non-segregated mixture were assessed, reflecting the typical condition found in most hospitals.

Regardless of segregation, carbon and oxygen were the two predominant elements in HCW. They constitute approximately 85.7% of HCW-A1, about 86.9% of HCW-A4, around

28.9% of HCW-B, and approximately 73.0% of HCW-D. In the total non-segregated mixture, carbon and oxygen account for approximately 77.8% of the packaged mass.

The stoichiometric chemical compositions of HCW, both under segregation or non-segregation conditions, were achievable, and the calculus of the Radiation Dose Coefficients: KERMA-fluence and Mass Stopping Power coefficients at various energies were fulfill.

Current commercial sterilization processes typically use a maximum beam energy of 10 MeV, as higher energies would produce neutrons, increasing the cost of shielding. An uncertainty in dose absorption greater than 10%, as demonstrated, may compromise the efficacy of pathogen inactivation. Therefore, using water in dosimetric processes with photons, instead of a phantom material representing HCW, may not ensure the effectiveness of the process.

For electron beams, using water in the dosimetric process for an energy of 50 MeV would guarantee the minimum uncertainty in the calibrations; however, such energy is not yet feasible for implementation.

The comparison between the KERMA-fluence coefficient for X-ray and Electron Mass Stopping Power for HCW and water media demonstrated that water is not a good substitute for HCW in the composition of simulator objects for dosimetric purposes using current sterilization equipment that provides a maximum energy of 10 MeV.

The percentage difference between the Radiation Dose Coefficient KERMA-fluence coefficient and the Mass Stopping Power of HCW and water, both being irradiated with energy up to 10 MeV, varies more than 10.0%; and these materials have a large difference in mass density, implying a great variation in the energy fluence profile in these two media.

By using information such as HCW density and composition, it becomes feasible to computationally simulate and analyze the energy deposition within the HCW package through the absorbed dose; utilizing particle transport software, KERMA-fluence, and Mass

Stopping Power coefficients. These simulations will be able to provide information on additional physical characteristics of these materials, such as the percentage of depth dose (PDD) inside the HCW and thus determine the most effective beam energy in the HCW irradiation process for treatments of the given HCW density. These analyses will determine the technical and economic feasibility of using radiation sterilization as a method of treating HCW, either as a substitute for or in conjunction with current treatment techniques for pathogenic inactivation.

CONFLICT OF INTEREST

The authors declare that they have no competing financial interests or personal relationships that may have influenced the work reported in this study.

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