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Radiative Stopping Power Calculations of Electrons over the 1 keV-1 GeV Energy Range in Some Biological Materials

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Abstract

Mass radiative stopping power calculations for incident electrons were performed over the 1 keV to 1 GeV energy range using analytical formulas derived from several theoretical models. The Rohrlich-Carlson formula was employed to calculate mass collision stopping powers, and the resulting values were subsequently incorporated into the mass radiative stopping power calculations. The Fano model was selected to account for the density effect correction. Amorphous carbon (C) and oxygen (O_2) were selected as simple materials, while compound materials included testicular and prostate tissues. The calculations were performed by implementing all equations described in this study within a custom computational code. The resulting values were compared with reference data from the ESTAR program and PENELOPE Monte Carlo simulations. For each target material and over its respective energy range, the formula introduced by Bhabha was evaluated for different values of n. The best-fitting values were 575, 800, 625, and 615 for amorphous carbon, oxygen, testicular tissue, and prostate tissue, respectively. When the variation of n with target material was taken into account, the calculated radiative stopping powers agreed most closely with the reference data (PENELOPE and ESTAR) in the high-energy range. This is expected, since most of these models were proposed and validated for energies above 0.5 MeV. Accordingly, the Bhabha formula can be recommended for calculating the radiative stopping power of electrons in arbitrary target materials at energies above 0.5 MeV. Furthermore, the evaluated dataset may serve as an input resource for dose calculations of light charged particles (electrons) in human tissue.

Subject Areas

Applied Physics

Keywords

Electron, Collision Stopping Power, Radiative Stopping Power, Density Effect Correction, Human Tissue

1. Introduction

As a charged particle moves through a material, it interacts primarily through Coulomb forces with the negatively charged electrons and positively charged nuclei that constitute the atoms of that material. As a result of these interactions, the charged particle continuously loses energy and eventually stops after traversing a finite distance. The average energy loss of charged particles along their tracks is expressed as the stopping power. The total stopping power of electrons is generally divided into two components: the collision stopping power and the radiative stopping power.

Collision stopping power expresses the average energy loss per unit path length due to inelastic Coulomb collisions with bound atomic electrons of the medium, causing ionization and excitation. Radiative stopping power expresses the average energy loss per unit path length due to bremsstrahlung emission arising from interactions with the electric fields of atomic nuclei and atomic electrons. The collision stopping power of light charged particles was first calculated by Bohr using classical arguments. Subsequently, several theories of collision stopping power were developed, some based on quantum mechanics, as formulated by Bethe and Bloch, and others based on dielectric response theory, as developed by Lindhard (1954) and Ritchie (1959) [1].

Over the years, numerous researchers have conducted both empirical and theoretical studies on the calculation of stopping power for electrons and positrons. Based on Bethe's theory (1930), the range and stopping power of electrons over the 1 keV-1000 MeV energy range have been calculated for various materials [2]. Electronic stopping power of electrons of 5 eV - 10 MeV energy range in some materials taking into account the concept of effective charge developed by Sugiyama (1985) and Rohrlich and Carlson (1954) has been calculated [3]. Stopping power and CSDA range of electrons and positrons of 100 eV - 1GeV energy range in some biological compounds have been calculated [4]. Stopping power and mean free path (MFP) of electrons of 20 eV - 10 keV energy range in some organic compounds have been calculated [5]. Stopping power of positrons of 50 eV - 10 MeV energy range in some organic compounds has been calculated [6]. A new formula for stopping power of electrons of 200 eV - 30 keV energy range for 37 solids has been developed [7]. Stopping power of electrons of low and medium energy range in some biological compounds has been calculated [8]. By using modified Bethe-Bloch stopping power formula and taking into account the effective charge concept, the stopping power and range of electrons of 5 eV - 10 MeV energy range in some human body tissues have been calculated [9]. By using the Bethe-Bloch stopping power formula, the stopping power and range of electrons of 0.01 MeV -

1000 MeV energy range in some target materials have been calculated [10]. Density effect correction of charged particles for various substances has been calculated and tabulated [11]. The primary objective of this work is to calculate the mass radiative stopping power of electrons over the energy range of 1 keV to 1 GeV in biological materials, including elemental carbon and oxygen, as well as compound tissues such as testicular and prostate tissue, using analytical formulas derived from various theoretical models. The calculated results are subsequently compared with available reference data to assess their accuracy and validity.

2. Materials and Methods

2.1. Mass Collision Stopping Power

The collision stopping power is due to the energy transfer from the incident particle to the bound atomic electrons of the medium. The mass collision stopping power of incident electrons at medium and high energies has been expressed as in Eq.1 [12]-[14].

$$\left(-\frac{\mathrm{d}E}{\rho \mathrm{d}x}\right)_{col} = k\frac{z^2 Z}{A\beta^2}\begin{Bmatrix}\ln\left(\frac{E}{I}\right)+\frac{1}{2}\ln\left(1+\frac{\tau}{2}\right)\\ +F^{-}(\tau)/2-\delta/2\end{Bmatrix} \quad (1)$$

Where,

$k = 4\pi r_e^2 N_a mc^2 = 0.307075$ MeV·cm²·mol⁻¹, β is the ratio of the velocity (v) of the incident particle to the speed of light ($\beta = v/c$). τ is the kinetic energy of the incident electron or positron in units of rest mass, E is the kinetic energy of the incident particle, A is the mass number of the target material, Z is the atomic number of the target material, I is the mean excitation energy of the target material, z is the charge of the incident particle, mc^2 is the electron rest mass energy ($mc^2 = 0.511$MeV). F(τ) is an energy dependent function and is expressed in Eq.2.

$$F^{-}(\tau) = \left(1-\beta^2\right)\left[1+\frac{\tau^2}{8}-(2\tau+1)\ln(2)\right] \quad (2)$$

2.2. Density Effect Correction

Density effect correction (δ), is a second correction term applied to the Bethe collision stopping power equation to account for the polarization or density effect in condensed media. The asymptotic formula of density effect correction at high energies was introduced by Fano as in Eq.3 [15] [16].

$$\delta = 2\ln\left(\frac{\hbar\omega_p}{I}\right)+\ln\left(\beta^2\gamma^2\right)-1.0 \quad (3)$$

$$\hbar\omega_p = 28.816\sqrt{\frac{\rho Z}{A}} \quad \gamma = \frac{1}{\sqrt{1-\beta^2}}$$

Where, $\hbar\omega_p$ is plazma energy (eV), γ is Lorentz factor and ρ is the density of target material in unit of (g/cm³).

2.3. Determination of *Z*, *A* and *I* of the Compounds

The mass collision stopping power and mass radiative stopping power calculations of the compounds were performed by considering its elemental compositions. The atomic number and mass number of each compound were determinated using additive rules given by Eqs. 4 and 5. Whereas, mean excitation energy of each compound were determinated using bragg-kleeman additive rule given by Eq. 6 [11] [16].

$$A_{\text{compound}} = \sum_i W_i \left(A_i \right) \tag{4}$$

$$Z_{\text{compound}} = \left[\frac{\sum_i \left(W_i / A_i \right) Z_i^2}{\sum_i \left(W_i / A_i \right) Z_i} \right] \tag{5}$$

$$I_{\text{compound}} = \exp \left[\frac{\sum_i W_i \left(Z_i / A_i \right) \ln \left(I_i \right)}{\sum_i W_i \left(Z_i / A_i \right)} \right] \tag{6}$$

Where, W_i, Z_i, A_i and I_i are respectively weight fraction, atomic number, mass number and mean excitation energy of i element in the compound target.

2.4. Mass Radiative Stopping Power

When an electron is deflected by scattering from a nucleus or from an atomic electron, it is briefly accelerated and can emit radiation. Its accompanying energy loss is the radiative stopping power of the target material, and is known as Bremsstrahlung. There are many analytical expressions used for radiative stopping power calculations.

For high energy ($E >> m_0c^2$) the ratio of radiative stopping power to collision stopping power of electrons introduced by Bhabha in 1938 is given in Eq.7 [17] [18].

$$\frac{\left(-\frac{\mathrm{d}E}{\rho \mathrm{d}x} \right)_{rad}}{\left(-\frac{\mathrm{d}E}{\rho \mathrm{d}x} \right)_{col}} = \frac{EZ}{n} \tag{7}$$

Where, Z is atomic number of the target material, E is kinetic energy of incident electron in MeV and n is a constatnt variously taken to be 700 or 800 MeV.

Another general formula of the mass radiative stopping power for high energies (complete screening, $\tau \gg 1/\alpha z^{1/3}$) based on quantum-mechanical theories was introduced by Bethe and Heitler in 1934 is given in Eq. 8 [18] [19].

$$\left(-\frac{dE}{\rho dx} \right)_{rad} = \frac{4 r_e^2 \alpha}{\beta^2} N_A \frac{Z\left(Z+1 \right)}{A} \cdots \left\{ \left(\tau + 1 \right) m_0 c^2 \ln \left(\frac{183}{Z^{1/3}} + \frac{1}{18} \right) \right\} \tag{8}$$

$$r_e = \frac{e^2}{m_0 c^2} = 2.818 \times 10^{-13} \left(\text{cm}\right) \quad \alpha = 1/137.035$$

Where, Z is atomic number of target material, α is fine structure constant, r_e is classical radius of electron, N_A is avogadro number, τ is the kinetic energy of the incident electron in units of rest mass, m_0c^2 is the electron rest mass energy (0.511 MeV).

Considering the Bremsstrahlung and radiation length X_0 (Z), one of the expressions used for mass radiative stopping power calculations was first introduced by Bethe and Heitler (1934) and modified by Wheeler and Lamb in 1939 is given in Eq.9 [20] [21].

$$\left(-\frac{\mathrm{d}E}{\rho \mathrm{d}x}\right)_{rad} = \frac{E}{X_0\left(Z\right)} \tag{9}$$

$$\frac{1}{X_0\left(Z\right)} = \frac{4r_e^2 \alpha N_A}{A} Z\left(Z+1\right) \ln\left(\frac{183}{Z^{1/3}}\right) \tag{10}$$

Where, Z, α, r_e and N_A were defined before as in Eq.8.

Considering the Bremsstrahlung and radiation length X_0 (Z), another expression used for mass radiative stopping power calculations introduced by Tsai in 1974 is given in Eq.11 [4] [22] [23].

$$\left(-\frac{\mathrm{d}E}{\rho \mathrm{d}x}\right)_{rad} = \frac{E}{X_0\left(Z\right)} \tag{11}$$

Where, E is the kinetic energy of the incident particle (electron) in MeV, X_0 (Z) is called the radiation length and is given in Eq. 12.

$$X_0\left(Z\right) = 716.405\mathrm{A} \Big/ \left[Z^2\left(L_{rad} - f\left(Z\right)\right) + ZL'_{rad}\right] \tag{12}$$

Where, Z is atomic number of target material, $f(z)$ is an atomic number dependent function and is expressed in Eq. 13. The L_{rad} and L'_{rad} values are given in **Table 1**.

Table 1. L_{rad} and L'_{rad} values related to values of Z.

Element	Z	L_{rad}	L'_{rad}
H	1	5.31	6.144
He	2	4.79	5.621
Li	3	4.74	5.805
Be	4	4.71	5.924
Others	>4	$L_{rad} = \ln\left(184.15Z^{-1/3}\right)$	$L'_{rad} = \ln\left(1194Z^{-2/3}\right)$

$$f\left(Z\right) = a^2\left[\left(1+a^2\right)^{-1} + 0.20206 - 0.0369a^2 + 0.0083a^4 - 0.002a^6\right] \tag{13}$$

$$a = \alpha Z \quad \alpha = 1/137.035$$

Table 2. Material composition of testicular and prostate tissues (ICRU, 1992).

Weight Fractions		
Element	**Testes**	**Prostate**
H	0.106	0.105
C	0.099	0.256
O	0.020	0.027
N	0.766	0.602
Na	0.002	0.001
P	0.001	0.002
S	0.002	0.003
Cl	0.002	0.002
K	0.002	0.002
Density (g/cm^3)	1.040	1.045

3. Results and Discussion

The mass radiative stopping power of electrons over the 1 keV m- 1 GeV energy range in amorphous carbon, oxygen, testicular tissue, and prostate tissue was calculated and tabulated (Tables 3-6) using analytical equations from different models.

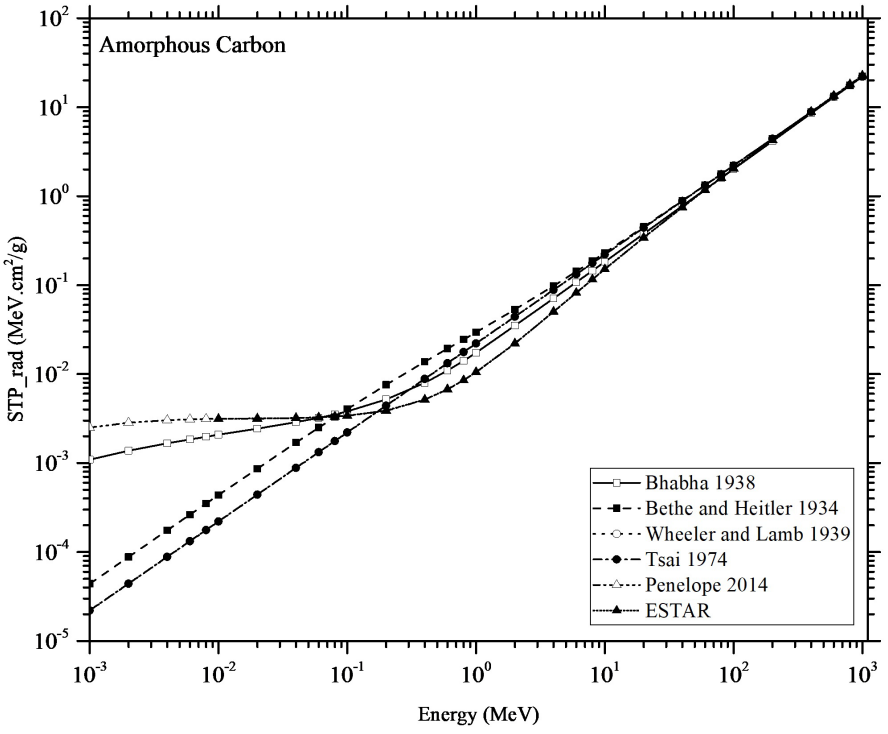


Figure 1. Mass radiative stopping power in amorphous carbon as a function of incident electron energy.

The obtained results were plotted (Figures 1-4) and compared with one another, as well as with results from the ESTAR program and the PENELOPE Monte Carlo code [24]-[26]. The material composition and density of testicular and prostate tissues used as target materials were obtained from ICRU (1992) (Table 2).

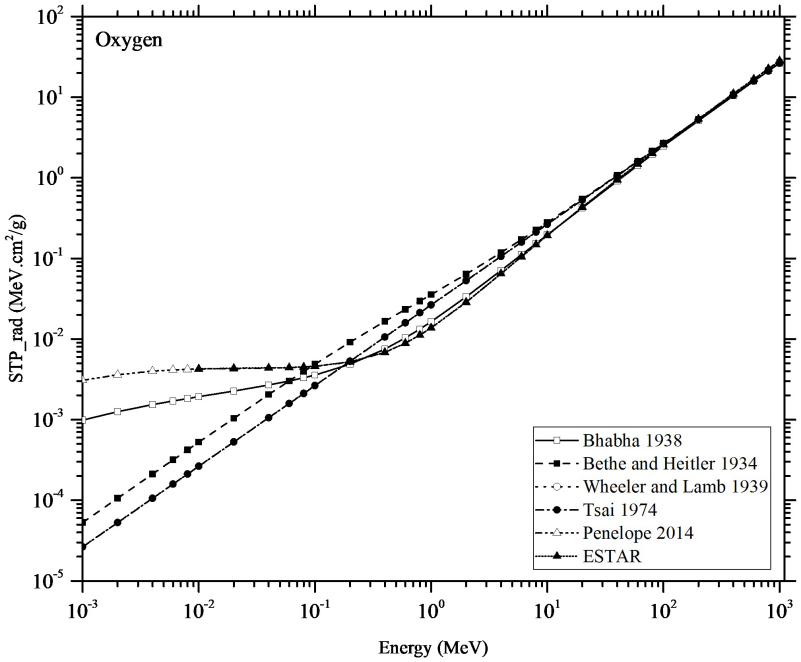


Figure 2. Mass radiative stopping power in oxygen as a function of incident electron energy.

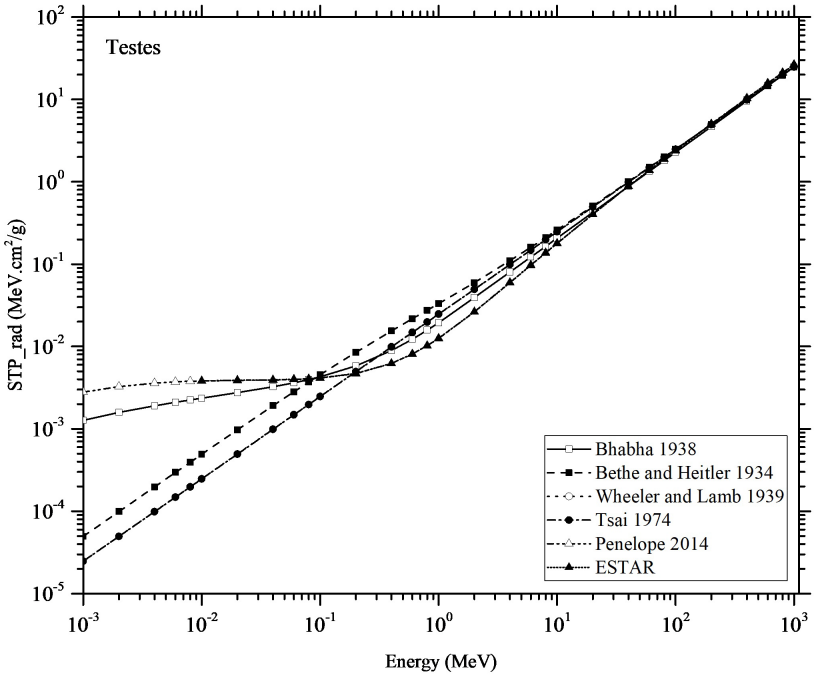


Figure 3. Mass radiative stopping power in testicular tissue as a function of incident electron energy.

For each target material and over the respective energy range, Eq. (7) was evaluated for different values of n, and the best-fitting values that yielded results closest to the reference data was were found to be 575, 800, 625, and 615 for amorphous carbon, oxygen, testicular tissue, and prostate tissue, respectively.

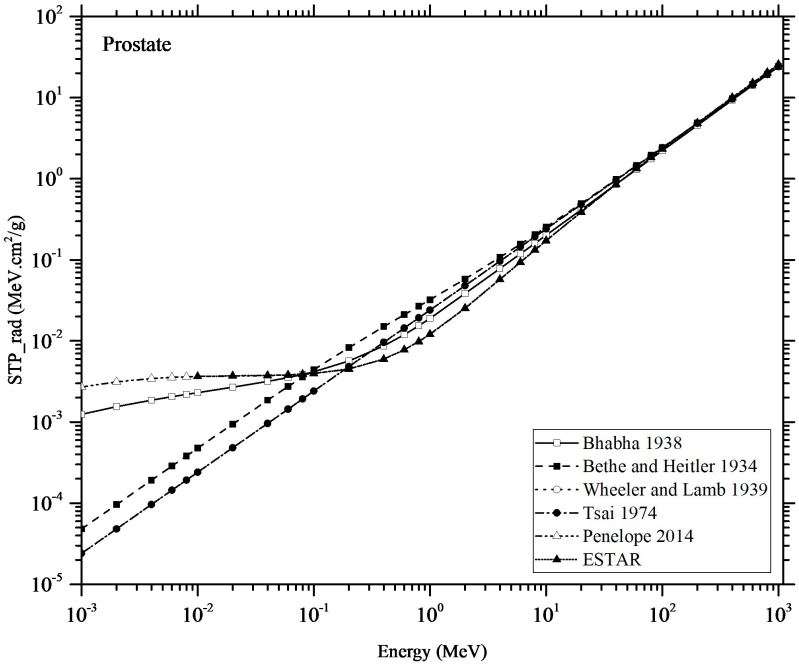


Figure 4. Mass radiative stopping power in prostate tissue as a function of incident electron energy.

The obtained values of n were employed in the mass radiative stopping power calculations for the corresponding target materials. As shown in Figures 1-4, a clear discrepancy between the reference and calculated data was observed for energies below 0.5 MeV, with this difference becoming more pronounced at lower energies. Furthermore, as the energy increases, the difference between the calculated and reference data decreases. The results obtained using the formula introduced by Bhabha were found to be closest to the reference data, and the corresponding curves exhibited similar behavior (Figures 1-4). In addition, the radiative stopping power formulas introduced by Bethe and Heitler, Wheeler and Lamb, and Tsai were based on a linear fit, with the results from the latter two (Wheeler and Lamb, and Tsai) found to be very close to each other.

Table 3. Mass radiative stopping power results of electrons in amorphous carbon.

Energy (MeV)	STP_rad (MeV.cm²/g)					
	Bhabha, 1938	Bethe and Heitler, 1934	Wheeler and Lamb, 1939	Tsai, 1974	Penelope 2014	ESTAR
0.001	0.00109	0.00004	0.00002	0.00002	0.00251	-
0.002	0.00138	0.00009	0.00004	0.00004	0.00284	-

Continued

0.004	0.00167	0.00017	0.00009	0.00009	0.00304	-
0.006	0.00185	0.00026	0.00013	0.00013	0.00310	-
0.008	0.00198	0.00035	0.00017	0.00017	0.00313	-
0.01	0.00208	0.00043	0.00022	0.00022	0.00314	0.00315
0.02	0.00244	0.00086	0.00044	0.00044	0.00316	0.00318
0.04	0.00288	0.00170	0.00088	0.00088	0.00320	0.00322
0.06	0.00322	0.00251	0.00132	0.00133	0.00326	0.00327
0.08	0.00353	0.00329	0.00176	0.00177	0.00333	0.00334
0.1	0.00382	0.00405	0.00220	0.00221	0.00340	0.00341
0.2	0.00519	0.00758	0.00441	0.00442	0.00387	0.00390
0.4	0.00798	0.01377	0.00882	0.00885	0.00516	0.00517
0.6	0.01097	0.01931	0.01323	0.01327	0.00675	0.00676
0.8	0.01412	0.02451	0.01764	0.01770	0.00855	0.00856
1	0.01741	0.02951	0.02204	0.02212	0.01052	0.01053
2	0.03518	0.05307	0.04409	0.04424	0.02209	0.02213
4	0.07088	0.09818	0.08818	0.08848	0.05030	0.05026
6	0.10777	0.14267	0.13227	0.13272	0.08213	0.08193
8	0.14534	0.18698	0.17636	0.17696	0.11608	0.11580
10	0.18337	0.23120	0.22045	0.22119	0.15149	0.15130
20	0.37774	0.45195	0.44090	0.44239	0.34130	0.34170
40	0.77791	0.89305	0.88181	0.88478	0.74912	0.75080
60	1.18650	1.33410	1.32270	1.32720	1.17402	1.17500
80	1.60060	1.77510	1.76360	1.76960	1.60837	1.60800
100	2.01870	2.21600	2.20450	2.21190	2.04888	2.04600
200	4.14870	4.42090	4.40900	4.42390	4.29506	4.27600
400	8.51950	8.83050	8.81810	8.84780	8.85980	8.82000
600	12.97400	13.24000	13.22700	13.27200	13.46000	13.40000
800	17.48300	17.65000	17.63600	17.69600	18.07680	18.01000
1000	22.03200	22.05900	22.04500	22.11900	22.70830	22.62000

Table 4. Mass radiative stopping power results of electrons in oxygen.

Energy (MeV)	STP_rad (MeV.cm²/g)					
	Bhabha, 1938	Bethe and Heitler, 1934	Wheeler and Lamb, 1939	Tsai, 1974	Penelope 2014	ESTAR
0.001	0.00098	0.00005	0.00002	0.00002	0.00307	-
0.002	0.00126	0.00010	0.00005	0.00005	0.00361	-
0.004	0.00154	0.00021	0.00010	0.00010	0.00400	-

Continued

0.006	0.00171	0.00031	0.00016	0.00016	0.00415	-
0.008	0.00183	0.00042	0.00021	0.00021	0.00422	-
0.01	0.00193	0.00052	0.00026	0.00026	0.00426	0.00427
0.02	0.00227	0.00104	0.00053	0.00052	0.00431	0.00434
0.04	0.00269	0.00205	0.00106	0.00106	0.00436	0.00438
0.06	0.00302	0.00302	0.00159	0.00159	0.00442	0.00443
0.08	0.00331	0.00396	0.00213	0.00211	0.00450	0.00451
0.1	0.00358	0.00488	0.00266	0.00264	0.00459	0.00461
0.2	0.00487	0.00913	0.00531	0.00529	0.00519	0.00522
0.4	0.00751	0.01659	0.01063	0.01057	0.00684	0.00686
0.6	0.01033	0.02327	0.01594	0.01586	0.00888	0.00890
0.8	0.01332	0.02954	0.02125	0.02115	0.01121	0.01122
1	0.01643	0.03555	0.02656	0.02643	0.01374	0.01376
2	0.03336	0.06395	0.05313	0.05287	0.02861	0.02869
4	0.07096	0.11831	0.10626	0.10573	0.06473	0.06471
6	0.11123	0.17192	0.15938	0.15860	0.10525	0.10510
8	0.15317	0.22531	0.21251	0.21146	0.14839	0.14820
10	0.19631	0.27861	0.26564	0.26433	0.19338	0.19320
20	0.42365	0.54462	0.53128	0.52865	0.43319	0.43430
40	0.91050	1.07620	1.06260	1.05730	0.94666	0.95020
60	1.42150	1.60760	1.59380	1.58600	1.47989	1.48400
80	1.94810	2.13900	2.12510	2.11460	2.02409	2.02800
100	2.48640	2.67040	2.65640	2.64330	2.57597	2.57700
200	5.10050	5.32730	5.31280	5.28650	5.38527	5.37100
400	10.41400	10.64100	10.62600	10.57300	11.08670	11.05000
600	15.80800	15.95500	15.93800	15.86000	16.82420	16.78000
800	21.25400	21.26900	21.25100	21.14600	22.58370	22.52000
1000	26.73800	26.58200	26.56400	26.43300	28.35210	28.27000

Table 5. Mass radiative stopping power results of electrons in testes tissue.

Energy (MeV)	**STP_rad (MeV.cm²/g)**					
	Bhabha, 1938	Bethe and Heitler, 1934	Wheeler and Lamb, 1939	Tsai, 1974	Penelope 2014	ESTAR
0.001	0.00127	0.00005	0.00002	0.00002	0.00279	-
0.002	0.00159	0.00010	0.00005	0.00005	0.00325	-
0.004	0.00191	0.00020	0.00010	0.00010	0.00359	-
0.006	0.00210	0.00030	0.00014	0.00014	0.00372	-

Continued

0.008	0.00225	0.00040	0.00019	0.00019	0.00378	-
0.01	0.00236	0.00049	0.00024	0.00025	0.00382	0.00383
0.02	0.00275	0.00097	0.00049	0.00049	0.00387	0.00389
0.04	0.00324	0.00191	0.00099	0.00098	0.00392	0.00394
0.06	0.00363	0.00282	0.00149	0.00148	0.00398	0.00400
0.08	0.00397	0.00370	0.00198	0.00198	0.00405	0.00407
0.1	0.00429	0.00455	0.00248	0.00247	0.00414	0.00416
0.2	0.00581	0.00852	0.00496	0.00495	0.00470	0.00473
0.4	0.00893	0.01547	0.00991	0.00989	0.00622	0.00624
0.6	0.01226	0.02171	0.01487	0.01484	0.00811	0.00813
0.8	0.01578	0.02755	0.01982	0.01979	0.01025	0.01027
1	0.01945	0.03316	0.02478	0.02473	0.01259	0.01260
2	0.03937	0.05965	0.04955	0.04946	0.02632	0.02638
4	0.08019	0.11035	0.09911	0.09892	0.05976	0.05969
6	0.12186	0.16036	0.14866	0.14838	0.09733	0.09710
8	0.16427	0.21015	0.19822	0.19785	0.13739	0.13710
10	0.20719	0.25986	0.24777	0.24731	0.17918	0.17880
20	0.42647	0.50797	0.49554	0.49461	0.40243	0.40280
40	0.87757	1.00370	0.99108	0.98923	0.88149	0.88290
60	1.33790	1.49940	1.48660	1.48380	1.37967	1.38100
80	1.80430	1.99510	1.98220	1.97850	1.88843	1.88700
100	2.27510	2.49070	2.47770	2.47310	2.40450	2.40000
200	4.67260	4.96890	4.95540	4.94610	5.03335	5.00800
400	9.58930	9.92510	9.91080	9.89230	10.37130	10.32000
600	14.59800	14.88100	14.86600	14.83800	15.74540	15.67000
800	19.66600	19.83800	19.82200	19.78500	21.14060	21.04000
1000	24.77900	24.79400	24.77700	24.73100	26.54610	26.43000

Table 6. Mass radiative stopping power results of electrons in prostate tissue.

Energy (MeV)	STP_rad (MeV.cm²/g)					
	Bhabha, 1938	Bethe and Heitler, 1934	Wheeler and Lamb, 1939	Tsai, 1974	Penelope 2014	ESTAR
0.001	0.00125	0.00005	0.00002	0.00002	0.00270	-
0.002	0.00155	0.00009	0.00005	0.00004	0.00313	-
0.004	0.00187	0.00019	0.00009	0.00009	0.00344	-
0.006	0.00206	0.00028	0.00014	0.00014	0.00356	-
0.008	0.00220	0.00038	0.00019	0.00019	0.00362	-
0.01	0.00231	0.00047	0.00024	0.00024	0.00365	0.00366

Continued

0.02	0.00269	0.00094	0.00048	0.00048	0.00369	0.00372
0.04	0.00317	0.00186	0.00096	0.00096	0.00374	0.00376
0.06	0.00354	0.00274	0.00145	0.00144	0.00380	0.00382
0.08	0.00387	0.00359	0.00193	0.00193	0.00388	0.00389
0.1	0.00418	0.00443	0.00241	0.00241	0.00396	0.00398
0.2	0.00567	0.00828	0.00482	0.00482	0.00450	0.00453
0.4	0.00871	0.01505	0.00964	0.00963	0.00597	0.00599
0.6	0.01196	0.02111	0.01446	0.01445	0.00778	0.00780
0.8	0.01539	0.02679	0.01928	0.01926	0.00985	0.00986
1	0.01897	0.03225	0.02409	0.02408	0.01210	0.01211
2	0.03839	0.05801	0.04819	0.04816	0.02533	0.02539
4	0.07802	0.10731	0.09638	0.09632	0.05756	0.05750
6	0.11857	0.15594	0.14457	0.14448	0.09381	0.09358
8	0.15984	0.20436	0.19276	0.19264	0.13247	0.13210
10	0.20160	0.25270	0.24095	0.24080	0.17280	0.17240
20	0.41495	0.49398	0.48190	0.48160	0.38844	0.38870
40	0.85388	0.97611	0.96380	0.96319	0.85140	0.85250
60	1.30180	1.45810	1.44570	1.44480	1.33308	1.33400
80	1.75560	1.94010	1.92760	1.92640	1.82512	1.82300
100	2.21370	2.42210	2.40950	2.40800	2.32421	2.31900
200	4.54650	4.83200	4.81900	4.81600	4.86730	4.84200
400	9.33060	9.65180	9.63800	9.63190	10.03210	9.97700
600	14.20400	14.47200	14.45700	14.44800	15.23300	15.16000
800	19.13600	19.29100	19.27600	19.26400	20.45430	20.36000
1000	24.11000	24.11100	24.09500	24.08000	25.68660	25.57000

4. Conclusions

In this work, mass radiative stopping power calculations for incident electrons were performed over the 1 keV - 1 GeV energy range in selected elements and compounds using analytical equations derived from several theoretical models. Amorphous carbon and oxygen were selected as representative simple materials, while testicular and prostate tissues were selected as compound materials of direct biological and clinical relevance. All governing equations were implemented in a custom-developed computational code, and the resulting values were systematically compared with one another, as well as with reference data from the ESTAR program and PENELOPE Monte Carlo simulations, in order to assess the accuracy and reliability of each analytical model.

Taking into account the variation of the parameter n with target material, the radiative stopping power values obtained using the formula introduced by Bhabha

showed the closest agreement with the reference data (PENELOPE and ESTAR) in the high-energy range. This is expected, as most of these models were proposed and validated for the high-energy range above 0.5 MeV. The Bhabha formula also consistently yielded the closest agreement with the reference data across all four investigated materials. It can therefore be recommended as a reliable and computationally efficient alternative to more resource-intensive Monte Carlo simulations for calculating the radiative stopping power of electrons in a wide range of target materials. Given that testicular and prostate tissues are biological (human) tissues of direct relevance to radiation dosimetry and radiotherapy, the evaluated stopping power data extend beyond simple elemental benchmarks and carry practical significance for medical physics applications. Accordingly, the dataset generated in this study can serve as a valuable input resource for dose calculations involving light-charged particles (electrons) in human tissue, with potential applications in treatment planning, radiation protection, and microdosimetry studies. Future work may extend this approach to a broader range of biological tissues and materials, as well as to other light-charged particles such as positrons, in order to further validate the generality of the Bhabha formula and support its integration into clinical dosimetry software.

Conflicts of Interest

The authors declare no conflicts of interest.

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