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Calculation of Mass Stopping Power and Range of Protons as Well as Important Radiation Quantities in Some Biological Human Bodyparts (Water, Muscle, Skeletal and Bone, Cortical)

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Abstract

In this work, the electronic mass stopping power and the range of protons in some biological human body parts (Water, Muscle, Skeletal and Bone, Cortical) were calculated in the energy range of protons 0.04 to 200 MeV using the theory of Bethe-Bloch formula as giving in the references. All these calculations were done using Matlab program. The data related to the densities, average atomic number to mass number $\left\langle \frac{Z}{A} \right\rangle$ and excitation energies for the present tissues and substances were collected from ICRU Report 44 (1989). The present results for electronic mass stopping powers and ranges were compared with the data of PSTAR and good agreements were found between them, especially at energies between 1 - 200 MeV for stopping power and 4 - 200 MeV for the range. Also in this study, several important quantities in the field of radiation, such as thickness, linear energy transfer (LET), absorbed dose, equivalent dose, and effective dose of the protons in the given biological human body parts were calculated at protons energy 0.04 - 200 MeV.

Keywords

Biological Human Bodyparts, Protons, Range, MatLab, PSTAR, Electronic Mass Stopping Power, LET, Absorbed Dose, Effective and Equivalent Dose

1. Introduction

In many fields, such as radiation dosimetry, radiation biology, and many others, radiation chemistry, radiotherapy, and nuclear physics, the stopping power, energy loss, rangestraggling, and equivalent dose rate of ions in the air, tissue, and polymers are very important. The use of protons or heavier ions as an alternative to external photon beams in radiotherapy is increasing, with the reason being that they preserve the target dose, ensure a higher dose delivered to the tumor, and can transfer energy in the form of a point shot through diseased tissue due to the Bragg curve [1]. The stopping power of charged particles has been measured using a variety of ways, including direct energyloss measurements through films, backscattering from thick substrates with deposited absorbing layers, gamma resonance shift measurements, self-supporting methods, and indirect verification of the stopping power based on alpha energy losses in the air have all been reported as methods for measuring the stopping power of charged particles. [2] [3] [4].

In the present work, the electronic mass stopping power and range of proton in some biological human body parts (Water, Muscle, Skeletaland Bone, Cortical) are calculated using the Bethe-Bloch formula as reported in the references.

As it is known in any therapeutic unit with protons, it needs to calculate the absorbed dose, the equivalent dose to the tissue, and the effective dose according to the energy of the protons. Therefore, in this work, a variety of radiation quantities such as thickness, absorbed dose, equivalent dose, and effective dose of the protons in Water, Muscle, Skeletal and Bone, Cortical were also computed in proton energy range 0.04 - 200 MeV.

2. Methods

2.1. Calculations of Electronic Mass Stopping Power

Bethe was the first person to use quantum mechanical studies on stopping power. The Bethe theory of stopping power is valid when the projectile's velocity surpasses the Bohr velocity. In Bethe's theory, the goal is assumed to be charged particle. In Bethe's approach to energy loss, the Born approximation is employed to represent inelastic collisions between heavy particles and atomic electrons. In this theory, the projectile heavy particle is as assumed to be structureless, whereas the target nucleus is assumed to be infinitely massive [4]. For the energy range 0.04 - 200 MeV, the Bethe mass stopping power equation [4] [5] [6] [7] was used:

$$-\frac{\mathrm{d}E}{\rho \mathrm{d}x}=\frac{5.08\times 10^{-31} z^2 n}{\beta^2 \rho}\left[F(\beta)-\ln I\right] \quad (1)$$

where β is v/c where v is the proton velocity and c is light velocity, I is the mean excitation energy and $F(\beta)$ is given by

$$F(\beta)=\ln\frac{1.02\times 10^{6}\beta^2}{1-\beta^2}-\beta^2 \quad (2)$$

n is calculated using the following relation:

$$n = N_{av}\rho\left\langle\frac{Z}{A}\right\rangle \tag{3}$$

where N_a Avogadro number, ρ is the density of substances and Z/A is the ratio of atomic number to the mass number of substances. The basic data for human body tissues are given in **Table 1**. The calculated mass stopping power of protons for Water, Muscle, Skeletal and Bone, Cortical are based on Bethe equation after substituting the constants from **Table 1**. In **Table 2** the compositions of the human tissues are given [8].

2.2. Calculations of Range

The range of a heavy particle is the straight distance it travels within the target. Light particles like electrons and positrons scatter widely throughout the path of targets due to their low mass, making it difficult to determine their journey duration. The path length of light particles has been calculated with remarkable success using Monte Carlo methods, which are based on a broad class of computational algorithms. On the other hand, heavy particles like protons have a practically straight line path length. The range of protons can be calculated using numerical integration methods. The Continuous Slowing Down Approximation (CSDA), on the other hand, is a straightforward and extensively used method for finding a variable's range. This study used a simple and standard method for calculating the range of heavy particles such as protons in the targets. The CSDA approach uses incident particles to constantly lose energy in the route of the targets. neglects energy loss fluctuations. The range, R for an incident proton in the CSDA method is given as [1] [4] [7]:

$$R = \int_{E_0}^{E_f}\frac{\mathrm{d}E}{MS(E)} \tag{4}$$

Table 1. Basic data for calculating mass stopping powers.

Substances	Density ρ (g/m^3)	$\langle Z/A\rangle$	n (electrons/m^3)	I (eV)
Water	1,000,000	0.555	3.341×10^{29}	75
Muscle, Skeletal	1,050,000	0.550	3.476×10^{29}	74.6
Bone, Cortical	1,920,000	0.51	5.894×10^{29}	112

Table 2. Elemental composition of Water, Muscle, Skeletal and Bone, Cortical tissues.

Substances	Composition
Water	H(0.111898), O(0.888102)
Muscle, Skeletal	C(0.143000), N(0.034000), H(0.102000), O(0.710000), Na(0.001000), P(0.002000), k(0.004000), Cl(0.001000), S(0.003000)
Bone, Cortical	C(0.155000), N(0.042000), H(0.034000), O(0.435000), Na(0.001000), P(0.103000), S(0.003000), Ca(0.225000), Mg(0.002000)

where, E_0 is the initial energy of incident charged particle in material, E_f is the final energy of incident charged particle in material and $MS(E)$ is the mass stopping power.

2.3. Calculations of Thickness, Absorbed Dose, Equivalent Dose and Effective Dose

Thickness of proton in the tissue or substance is given by

$$T = \frac{R}{\rho} \tag{5}$$

where R (in g/cm^2) is the range and is ρ the density of the tissue or substance [9]

Absorbed dose in (in rad): It is the transfer of an amount of energy of 100 erg per gram of the absorbent material when protons pass over it and is given by the following relation: [9]

$$D = \frac{E}{1\ \text{grm}} \frac{1.6\times10^{-13}\ \text{J}}{1\ \text{MeV}} \frac{10^{7}\ \text{erg}}{1\ \text{J}} \frac{1\ \text{rad}}{\frac{100\ \text{erg}}{\text{gram}}} \tag{6}$$

where E is the proton energy.

Equivalent dose: is given by

$$H_T = \sum_R W_R \times D \tag{7}$$

where D is the absorbed dose and W_R is the weighting factor of radiation (proton) [9]

Effective dose: is given by

$$E = \sum_T W_T H_T \tag{8}$$

where W_T is the weighting factor of tissue or substance [9];
where $W_T = 0.12$ for Water, Muscle, Skeletal and Bone, Cortical and $W_R = 5$ for protons [10].

2.4. The Percentage Error of Difference

The percentage error of difference for the mass stopping power and range of protons in given biological human body parts is calculated by

$$\%\ \text{error} = \frac{\text{PSTAR result} - \text{Present result}}{\text{PSTAR result}} \times 100 \tag{9}$$

3. Results and Discussion

The results of mass stopping power and range of protons in some biological human body parts (Water, Muscle, Skeletal and Bone, Cortical) are given in Table 3. In Figures 1-3 the mass stopping power of biological human body parts and their compositions are plotted using MathLab program and it is noted that the mass stopping power of all substances and tissues is approximately equal to t the average values of its compositions. The comparison between the present calculated electronic mass stopping powers and that of PSTAR program [8] are

Table 3. Values of electronicmass stopping power (in MeV cm^2/g) of Water, Muscle, Skeletal and Bone, Cortical tissues.

Proton energy (MeV)	Mass stopping power (in MeV cm^2/g)								
	Water			Muscle, Skeletal			Bone, Cortical		
	This work	PSTAR	Error%	This Work	PSTAR	Error%	This Work	PSTAR	Error%
0.04	290.8147	732.4	60.29	280.2840	763.9	63.31	−468.188	648.4	172.21
0.06	733.2987	805	8.91	721.4194	835.5	13.65	183.5666	708.7	74.09
0.08	837.0064	826	−1.33	825.5114	854.5	3.39	401.4380	726	44.71
0.1	847.7091	816.1	−3.87	836.9089	842.8	0.70	484.8158	718.4	32.51
0.2	700.4432	661.3	−5.912	692.5518	669.4	−3.46	496.5740	580.5	14.46
0.4	488.4735	471.9	−3.51	483.2825	466.3	−3.64	375.3311	394	4.74
0.6	379.5403	368	−3.14	375.5942	363.2	−3.41	299.7432	307	2.36
0.8	313.3203	303.9	−3.10	310.1025	300	−3.37	251.1486	254.9	1.47
1.0	268.4361	260.8	−2.93	265.7017	241	−10.25	217.2573	219.6	1.07
2.0	161.8006	158.6	−2.02	160.1849	156.8	−2.16	133.9751	135.5	1.13
4.0	94.6491	94.04	−0.65	93.7174	93.01	−0.76	79.6218	81.42	2.21
6.0	68.4376	68.58	0.21	67.7684	67.83	0.09	57.9867	59.76	2.97
8.0	54.1565	54.60	0.81	53.6292	54	0.69	46.0890	47.77	3.52
10.0	45.0727	45.67	1.31	44.6350	45.17	1.18	38.4770	40.08	3.99
20.0	25.2182	26.07	3.27	24.9752	25.78	3.12	21.7030	23.07	5.93
30.0	17.8345	18.76	4.93	17.6633	18.56	4.83	15.4082	16.67	7.57
40.0	13.9076	14.88	6.54	13.7744	14.72	6.42	12.0447	13.26	9.17
50.0	11.4484	12.45	8.05	11.3390	12.31	7.89	9.9320	11.11	10.60
60.0	9.7547	10.78	9.51	9.6615	10.66	9.37	8.4736	9.63	12.01
70.0	8.5127	9.55	10.86	8.4315	9.45	10.78	7.4023	8.55	13.42
80.0	7.5606	8.62	12.29	7.4886	8.53	12.21	6.5800	7.72	14.77
90.0	6.8062	7.88	13.63	6.7414	7.8	13.57	5.9276	7.06	16.04
100.0	6.1927	7.28	14.94	6.1338	7.21	14.93	5.3965	6.53	17.36
110.0	5.6835		-	5.6294		-	4.9553		-
120.0	5.2536		-	5.2036		-	4.5826		-
130.0	4.8856		-	4.8391		-	4.2632		-
140.0	4.5667		-	4.5234		-	3.9864		-
150.0	4.2877	5.44	21.18	4.2470	5.38	21.06	3.7440	4.89	23.44
160.0	4.0413		-	4.0029		-	3.5298		-
170.0	3.8221		-	3.7858		-	3.3392		-
180.0	3.6257		-	3.5912		-	3.1683		-
190.0	3.4486		-	3.4159		-	3.0142		-
200.0	3.2882	4.49	26.77	3.2570	4.44	26.64	2.8745	4.04	28.85

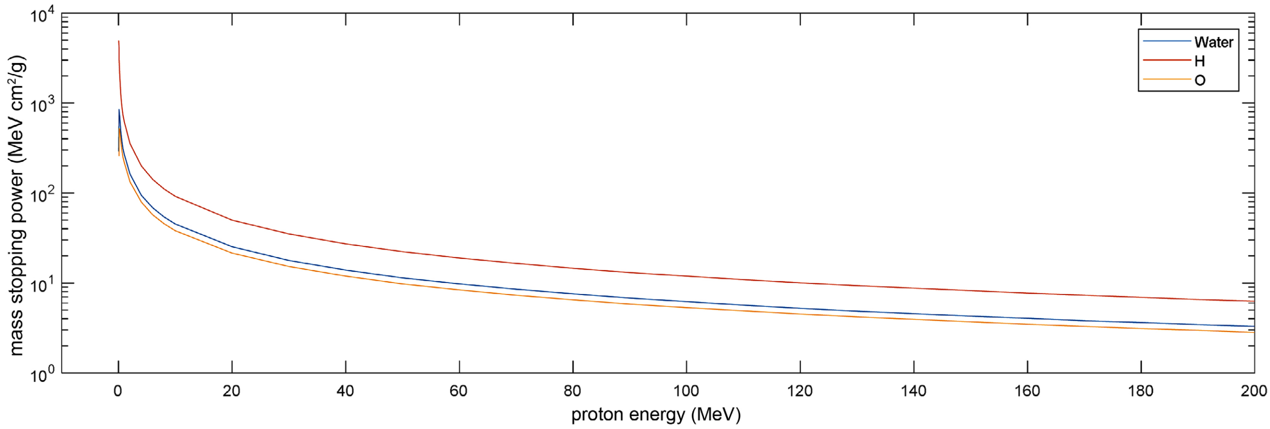

Figure 1. Mass stopping power of Water and its composition.

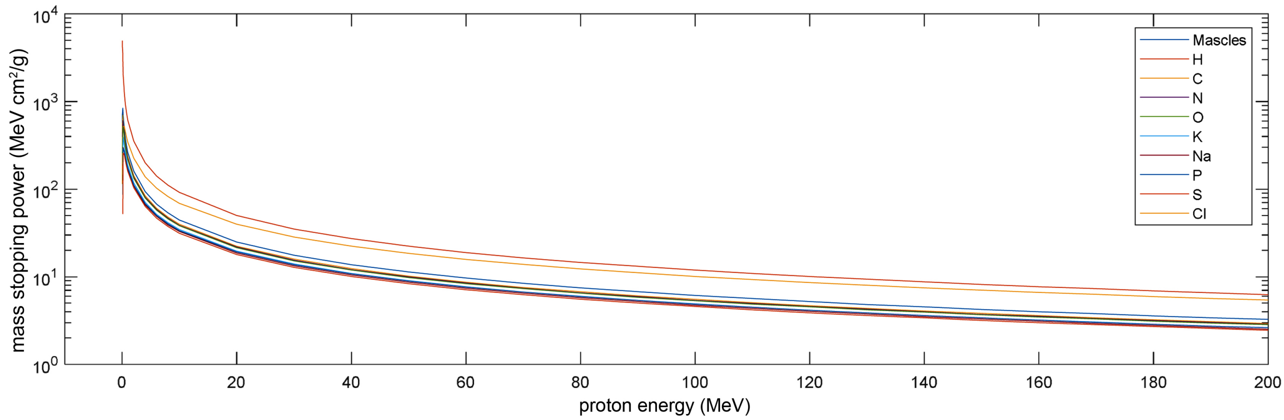

Figure 2. Mass stopping power of Muscle, Skeletal and its composition.

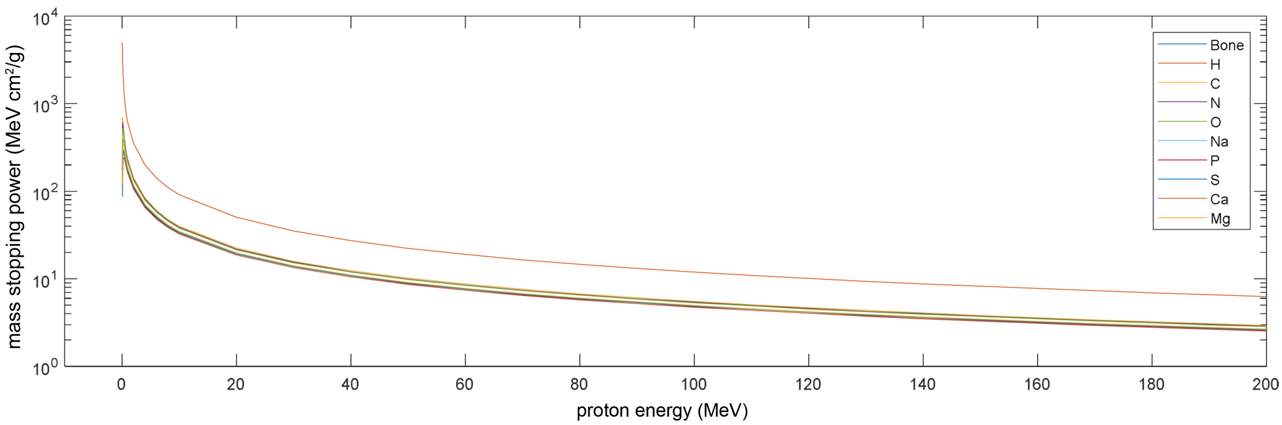

Figure 3. Mass stopping power of Bone, Cortical and its composition.

shown in Figures 4-6 angood agreements between two results are observed in energy range 1 - 200 MeV.

In Table 4 the ranges of protons in some Biological human body parts (Water, Muscle, Skeletal and Bone, Cortical) are given. In Figures 7-9 a comparison between present results of ranges and that of PSTAR data are shown in energy

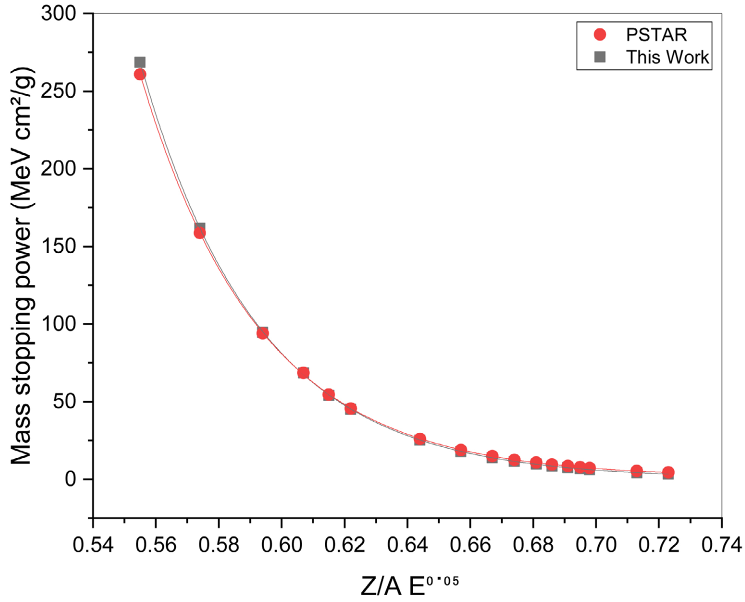

Figure 4. Mass stopping power of Water versus $\left\langle \frac{Z}{A} \right\rangle E^{0.05}$.

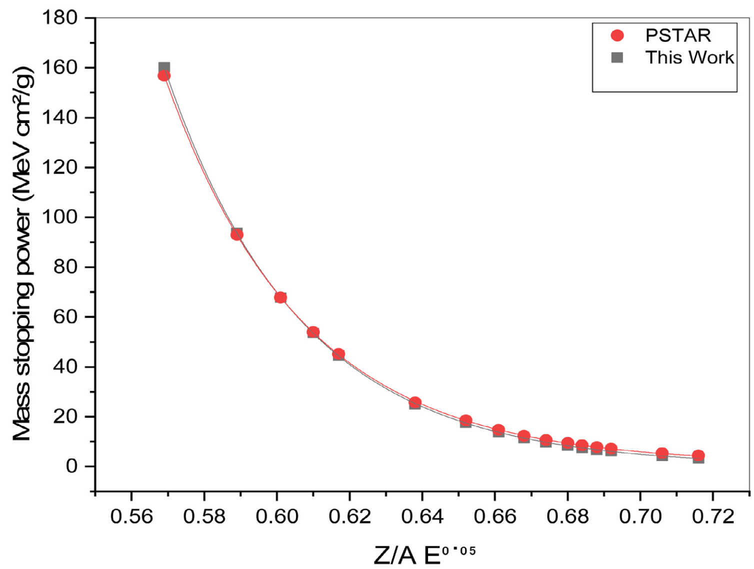

Figure 5. Mass stopping power of Muscle, Skeletal versus $\left\langle \frac{Z}{A} \right\rangle E^{0.05}$.

range 0.1 - 200 MeV and good agreements are observed. In Table 5 and Table 6 the thickness, LET, absorbed dose, effective and equivalent dose are given. In Table 7 and Table 8, the empirical formulae for calculating mass stopping powers and ranges for protons in some biological human body parts (Water, Muscle Skeletal and Bone, Cortical) are given with the percentage difference error.

4. Conclusion

In this work, calculations of mass stopping power and range of protons incident

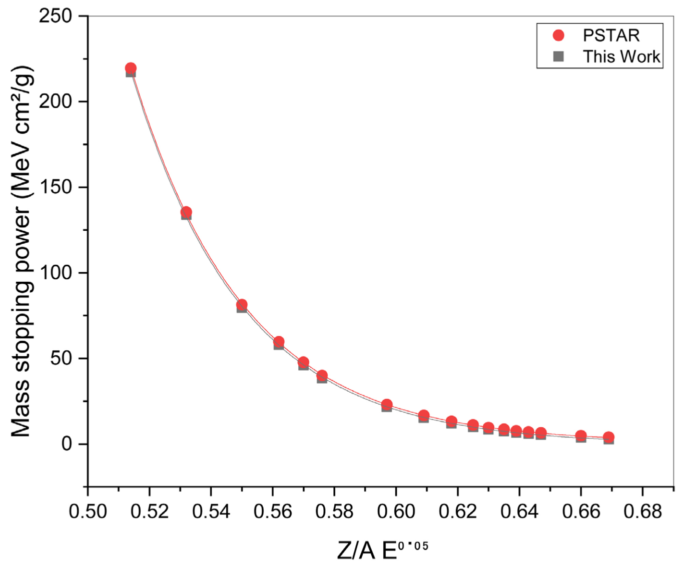

Figure 6. Mass stopping power of Bone, Cortical versus $\left\langle \frac{Z}{A} \right\rangle E^{0.05}$.

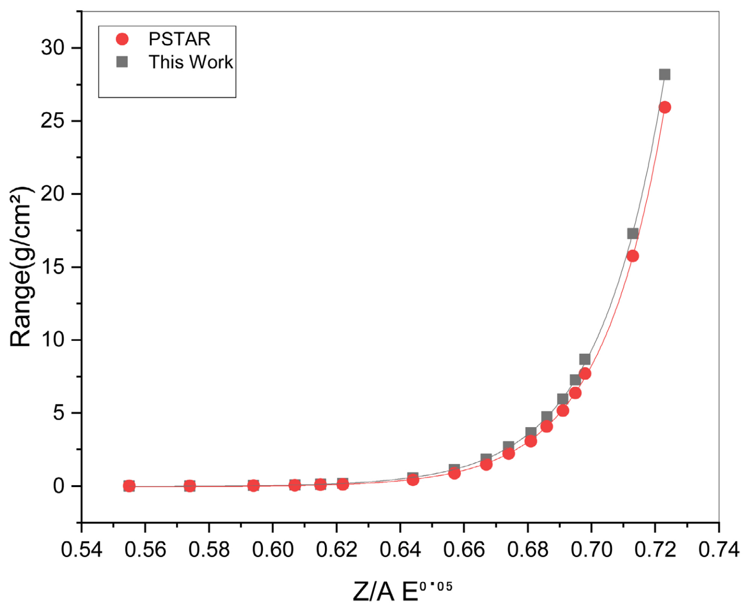

Figure 7. Range of Water versus $\left\langle \frac{Z}{A} \right\rangle E^{0.05}$.

on the three different biological human parts (Water, Muscle, Skeletal and Bone, Cortical) have been done and the following conclusions are drawn:

1) The mass stopping power of the Water, Muscle, Skeletal and Bone, and Cortical is equal to the average value of mass stopping power of their compositions in energy range 0.04 - 200 MeV.

2) Values for mass stopping power and ranges of protons in Water, Muscle, Skeletal and Bone, Cortical are in good agreement with the data of PSTAR program. The percentage value of error difference was between 0.09% - 28.88% for

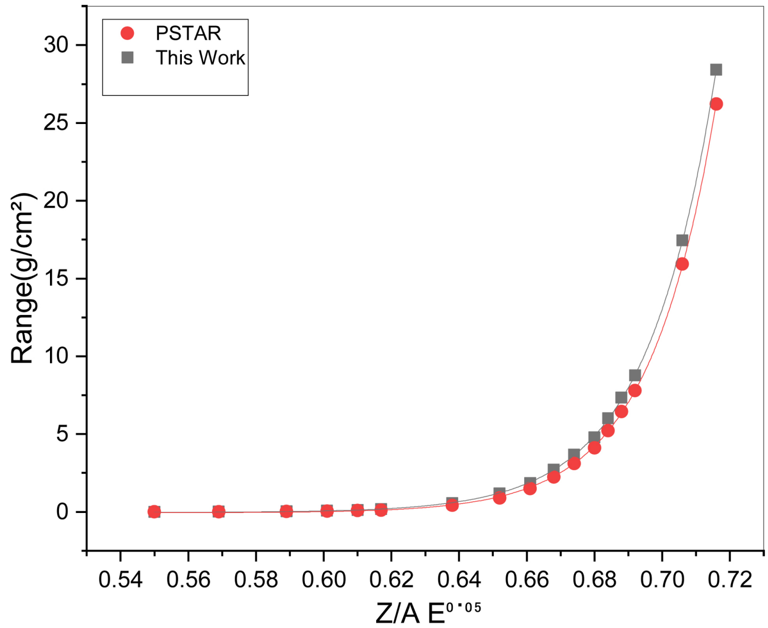

Figure 8. Range of Muscle, Skeletal versus $\left\langle \frac{Z}{A} \right\rangle E^{0.05}$.

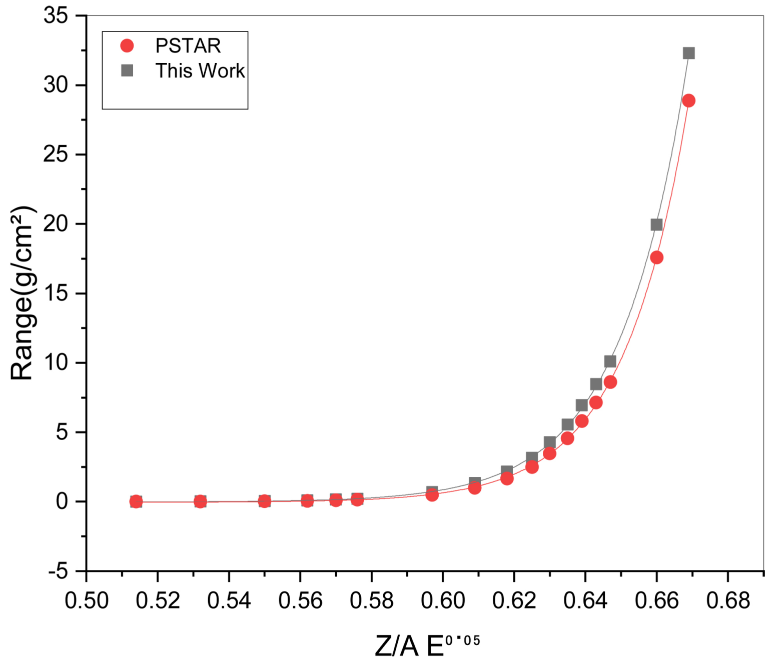

Figure 9. Range of Bone, Cortical versus $\left\langle \frac{Z}{A} \right\rangle E^{0.05}$

mass stopping power and was between 3.99% - 79.47% for range at proton energy ranging 0.04 - 200 MeV.

3) It was also observed that the maximum value of mass stopping power was at 0.1 MeV and after that, the mass stopping power start to decrease with increasing proton energy as expected.

Table 4. Values of range (in g/cm^2) of Water, Muscle, Skeletal and Bone, Cortical tissues.

Proton energy (MeV)	Range (g/cm^2)								
	Water			Muscle, Skeletal			Bone, Cortical		
	This Work	PSTAR	Error%	This Work	PSTAR	Error%	This Work	PSTAR	Error%
0.04	1.488×10^{-5}	7.25×10^{-5}	79.47	1.514×10^{-5}	6.96×10^{-5}	78.25	2.022×1^{-5}	7.86×10^{-5}	74.27
0.06	2.691×10^{-5}	9.78×10^{-5}	72.48	3.011×10^{-5}	9.39×10^{-5}	67.93	3.991×1^{-5}	1.06×10^{-4}	75.06
0.08	4.825×10^{-5}	1.21×10^{-4}	60.12	4.905×10^{-5}	1.17×10^{-4}	58.08	6.465×1^{-5}	1.34×10^{-4}	51.75
0.1	7.046×10^{-5}	1.45×10^{-4}	51.41	7.162×10^{-5}	1.40×10^{-4}	48.84	9.400×1^{-5}	1.61×10^{-4}	41.61
0.2	2.284×10^{-4}	2.80×10^{-4}	18.43	2.320×10^{-4}	2.71×10^{-4}	14.39	3.005×1^{-4}	3.13×10^{-4}	3.99
0.4	7.407×10^{-4}	6.42×10^{-4}	−10.33	7.518×10^{-4}	6.35×10^{-4}	−18.39	9.611×1^{-4}	7.37×10^{-4}	30.41
0.6	0.0015	0.0011	−36.36	0.0015	0.0012	−25.0	0.0019	0.0013	−46.15
0.8	0.0024	0.0017	−41.18	0.0024	0.0017	−41.18	0.0031	0.0020	−55.0
1.0	0.0035	0.0024	−45.83	0.0036	0.0024	−50.0	0.0045	0.0028	−60.71
2.0	0.011	0.0075	−46.67	0.0115	0.0075	−53.33	0.014	0.008	−75
4.0	0.036	0.024	−50.00	0.0373	0.024	−55.42	0.045	0.028	−60.72
6.0	0.073	0.049	−48.98	0.0743	0.050	−48.60	0.090	0.057	−57.91
8.0	0.119	0.082	−45.12	0.1210	0.083	−45.78	0.146	0.095	−53.69
10.0	0.174	0.11	−58.18	0.1766	0.12	−47.17	0.2124	0.14	−51.71
20.0	0.566	0.42	−34.76	0.572	0.42	−36.19	0.679	0.48	−41.46
30.0	1.126	0.88	−27.95	1.183	0.89	−32.92	1.340	0.99	−35.35
40.0	1.835	1.48	−23.99	1.854	1.50	−23.60	2.171	1.67	−30
50.0	2.680	2.22	−20.72	2.707	2.24	−20.85	3.157	2.50	−26.28
60.0	3.651	3.08	−18.54	3.688	3.12	−18.21	4.286	3.47	−23.51
70.0	4.743	4.07	−16.54	4.789	4.11	−16.52	5.551	4.57	−21.47
80.0	5.950	5.17	−15.09	6.007	5.23	−14.86	6.944	5.80	−19.73
90.0	7.266	6.38	−13.89	7.335	6.45	−13.72	8.460	7.15	−18.32
100.0	8.689	7.70	−12.84	8.770	7.79	−12.58	10.096	8.62	−17.12
110.0	10.214		-	10.309		-	11.845		-
120.0	11.840		-	11.949		-	13.706		-
130.0	13.562		-	13.686		-	15.675		-
140.0	15.380		-	15.519		-	17.750		-
150.0	17.290	15.76	−9.71	17.445	15.93	−9.51	19.927	17.58	−13.35
160.0	19.291		-	19.463		-	22.205		-
170.0	21.382		-	21.571		-	24.581		-
180.0	23.560		-	23.767		-	27.054		-
190.0	25.824		-	26.050		-	29.622		-
200.0	28.172	25.93	−8.65	28.417	26.21	−8.42	32.283	28.88	−11.78

Table 5. Thickness, LET, absorbed dose, equivalent dose and effective dose of proton in Water and Muscle, Skeletal.

(MeV)	Water					Macles, Skeletal				
	Thickness (cm)	LET (MeV/cm)	Absorbed Dose × 10^{-8} (rad)	Equivalent Dose × 10^{-8} (rem)	Effective Dose × 10^{-8} (rem)	Thickness (cm)	LET (MeV/cm)	Absorbed Dose × 10^{-8} (rad)	Equivalent Dose × 10^{-8} (rem)	Effective Dose × 10^{-8} (rem)
0.04	1.488×10^{-5}	290.8147	0.064	0.320	0.034	1.441×10^{-5}	294.298	0.064	0.320	0.034
0.06	2.691×10^{-5}	733.2987	0.096	0.480	0.057	2.868×10^{-5}	757.490	0.096	0.480	0.057
0.08	4.825×10^{-5}	837.0064	0.128	0.640	0.076	4.671×10^{-5}	866.787	0.128	0.640	0.076
0.1	7.046×10^{-5}	847.7091	0.160	0.800	0.096	6.821×10^{-5}	878.754	0.160	0.800	0.096
0.2	2.284×10^{-4}	700.4432	0.320	1.600	0.192	2.210×10^{-4}	727.179	0.320	1.600	0.192
0.4	7.407×10^{-4}	488.4735	0.640	3.200	0.384	7.160×10^{-4}	507.446	0.640	3.200	0.384
0.6	0.0015	379.5403	0.960	4.800	0.576	0.0014	394.373	0.960	4.800	0.576
0.8	0.0024	313.3203	1.280	6.400	0.768	0.0023	325.607	1.280	6.400	0.768
1.0	0.0035	268.4361	1.600	8	0.960	0.0034	278.986	1.600	8	0.960
2.0	0.011	161.8006	3.200	16	1.920	0.0110	168.194	3.200	16	1.920
4.0	0.036	94.6491	6.400	32	3.840	0.0356	98.403	6.400	32	3.840
6.0	0.073	68.4376	9.600	48	5.760	0.0707	71.156	9.600	48	5.760
8.0	0.119	54.1565	12.800	64	7.680	0.1152	56.310	12.800	64	7.680
10.0	0.174	45.0727	16	80	9.600	0.1682	46.866	16	80	9.600
20.0	0.566	25.2182	32	160	19.200	0.545	26.224	32	160	19.200
30.0	1.126	17.8345	48	240	28.800	1.084	18.546	48	240	28.800
40.0	1.835	13.9076	64	320	38.400	1.765	14.463	64	320	38.400
50.0	2.680	11.4484	80	400	48	2.578	11.905	80	400	48
60.0	3.651	9.7547	96	480	57.600	3.512	10.144	96	480	57.600
70.0	4.743	8.5127	112	560	67.200	4.561	8.853	112	560	67.200
80.0	5.950	7.5606	128	640	76.800	5.721	7.863	128	640	76.800
90.0	7.266	6.8062	144	720	86.400	6.986	7.078	144	720	86.400
100.0	8.689	6.1927	160	800	96	8.353	6.440	160	800	96
110.0	10.214	5.6835	176	880	105.60	9.818	5.910	176	880	105.60
120.0	11.840	5.2536	192	960	115.20	11.380	5.463	192	960	115.20
130.0	13.562	4.8856	208	1040	124.80	13.034	5.081	208	1040	124.80
140.0	15.380	4.5667	224	1120	134.40	14.780	4.749	224	1120	134.40
150.0	17.290	4.2877	240	1200	144	16.615	4.459	240	1200	144
160.0	19.291	4.0413	256	1280	153.60	18.537	4.203	256	1280	153.60
170.0	21.382	3.8221	272	1360	163.20	20.544	3.975	272	1360	163.20
180.0	23.560	3.6257	288	1440	172.80	22.635	3.770	288	1440	172.80
190.0	25.824	3.4486	304	1520	182.40	24.809	3.586	304	1520	182.40
200.0	28.172	3.2882	320	1600	192	27.064	3.419	320	1600	192

Table 6. Thickness, LET, absorbed dose, equivalent dose and effective dose of proton in Bone, Cortical.

E (MeV)	Bone, Cortical				
	Thickness (cm)	LET (MeV/cm)	Absorbed Dose × 10^{-8} (rad)	Equivalent Dose × 10^{-8} (rem)	Effective Dose × 10^{-8} (rem)
0.04	1.053×10^{-5}	−898.921	0.064	0.320	0.034
0.06	2.078×10^{-5}	352.447	0.096	0.480	0.057
0.08	3.367×10^{-5}	770.761	0.128	0.640	0.076
0.1	4.896×10^{-5}	930.846	0.160	0.800	0.096
0.2	1.565×10^{-4}	953.422	0.320	1.600	0.192
0.4	5.006×10^{-4}	720.635	0.640	3.200	0.384
0.6	9.881×10^{-4}	575.506	0.960	4.800	0.576
0.8	0.0016	482.205	1.280	6.400	0.768
1.0	0.0023	417.134	1.600	8	0.960
2.0	0.0074	257.232	3.200	16	1.920
4.0	0.023	152.873	6.400	32	3.840
6.0	0.047	111.334	9.600	48	5.760
8.0	0.076	88.490	12.800	64	7.680
10.0	0.110	73.875	16	80	9.600
20.0	0.353	41.669	32	160	19.200
30.0	0.698	29.583	48	240	28.800
40.0	1.131	23.125	64	320	38.400
50.0	1.644	19.069	80	400	48
60.0	2.232	16.269	96	480	57.600
70.0	2.891	14.212	112	560	67.200
80.0	3.616	12.633	128	640	76.800
90.0	4.406	11.380	144	720	86.400
100.0	5.258	10.361	160	800	96
110.0	6.169	9.514	176	880	105.60
120.0	7.138	8.798	192	960	115.20
130.0	8.164	8.185	208	1040	124.80
140.0	9.244	7.653	224	1120	134.40
150.0	10.378	7.188	240	1200	144
160.0	11.565	6.777	256	1280	153.60
170.0	12.802	6.411	272	1360	163.20
180.0	14.090	6.083	288	1440	172.80
190.0	15.428	5.787	304	1520	182.40
200.0	16.814	5.519	320	1600	192

Table 7. The empirical formulae for calculating mass stopping powers.

Substances	the empirical formulae for calculating mass stopping powers $y = A_1 e^{x/t_1} + y_o$	
	This work	PSTAR
Water	$A_1 = 7.13118 \times 10^8$ $t_1 = -0.03752$, $y_0 = 0.31402$ $R^2 = 0.99998$	$A_1 = 5.60379 \times 10^8$ $t_1 = -0.03805$, $y_o = 1.2486$ $R^2 = 0.99998$
Muscle, Skeletal	$A_1 = 6.760 \times 10^8$ $t_1 = -0.03729$, $y_0 = 0.17554$ $R^2 = 0.99999$	$A_1 = 5.2736 \times 10^8$, $t_1 = -0.03784$, $y_0 = 1.08913$ $R^2 = 0.99998$
Bone, Cortical	$A_1 = 3.12078 \times 10^8$ $t_1 = -0.03626$, $y_0 = -0.34842$ $R^2 = 1$	$A_1 = 2.99461 \times 10^8$, $t_1 = -0.03638$, $y_0 = 0.71424$ $R^2 = 1$

Table 8. The empirical formulae for calculating range.

Substances	the empirical formulae for calculating Range $y = A_1 e^{x/t_1} + y_o$	
	This work	PSTAR
Water	$A_1 = 2.33355 \times 10^{-14}$ $t_1 = 0.02082$, $y_0 = -0.03587$ $R^2 = 0.9999$	$A_1 = 6.50318 \times 10^{-15}$ $t_1 = 0.02013$, $y_0 = -0.05453$ $R^2 = 0.99988$
Muscle, Skeletal	$A_1 = 2.04888 \times 10^{-14}$ $t_1 = 0.02053$, $y_0 = -0.03963$ $R^2 = 0.99996$	$A_1 = 5.65636 \times 10^{-15}$ $t_1 = 0.01985$, $y_0 = -0.06137$ $R^2 = 0.99992$
Bone, Cortical	$A_1 = 2.054547 \times 10^{-14}$ $t_1 = 0.01924$, $y_0 = -0.03062$ $R^2 = 99986$	$A_1 = 5.09688 \times 10^{-15}$ $t_1 = 0.01844$, $y_0 = -0.04659$ $R^2 = 0.99988$

4) The empirical formulae suggested for mass stopping power are simple and accurate at proton energy (1 - 200 MeV) while the empirical formulae suggested for proton range give a good result compared to calculated values at proton energy (4 - 200 MeV).

5) Also in this study, some radiation quantities were calculated, such as linear energy transfer, adsorbed dose, and effective and equivalent dose that give good information to those interested in proton therapy.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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