

Mass Stopping Power and Range of Protons in Biological Human Body Tissues (Ovary, Lung and Breast)

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Abstract

In this work, the mass stopping power and range of protons in biological human body tissues (ovary, lung and breast) were calculated at the energy ranging from 0.04 MeV to 200 MeV using the MATLAB Program. The data relating to the densities, average atomic number to mass number $\left\langle \frac{Z}{A} \right\rangle$ and excitation energy for the present tissues were collected from ICRU Report 46. The mass stopping power was calculated by the Bethe formula. Moreover, the simple integration (continuous slowing down approximation) method was employed for calculating protons range at the tissues. The results of the mass stopping power versus energy and the range versus energy were presented graphically and the empirical formulae for calculating the mass stopping power and the ranges were obtained. The present results for mass stopping powers and ranges were compared with the results obtained by others. Good agreements were found between them, especially at the energy ranging from 3 to 200 MeV.

Keywords

Human Body Tissues, Protons, Range, MATLAB, Mass Stopping Power

1. Introduction

The stopping power and energy dissipation of charged particles through matter has been a subject of great interest for 100 years, because of its wide areas of application, such as ion implantation, fundamental particle physics, nuclear physics, radiation damage, radiology [1].

In recent years, the theoretical and experimental studies of the Stopping Power (SP) and range of charged particles have been increasing, especially in radiation physics. Many theoretical, as well as experimental studies have been established on this topic quite efficiently [2]. In particular, the use of protons or heavier ions are increasing as an alternative to external photon beams in radiotherapy, the reason is attributed to preserving the target dose, ensuring a higher dose delivered to the tumor and being able to transfer energy in the form of point shot through the diseased tissue due to the Bragg curve [3].

Charged particles are often used for radiotherapy because they have a well-defined penetration in tissues, the depth is dependent on the incident energy of particles and the nature of the irradiated material. Charged particles (protons, deuterons, alpha particles) have an important effect in radiotherapy as they have the ability to deliver their energy to the target [4].

For protons, the main contribution to the total stopping power is provided by the electronic stopping power which is based on inelastic collisions with the target's electrons. Conversely, the least contributing to the total stopping power comes from nuclear stopping power which arises from elastic collisions with the target's nucleons and is only significant at very low energy. For instance, the nuclear stopping power conduces more than one percent to the total stopping power only at energy below 20 KeV for protons [5]. Hence, precise knowledge of stopping power and range of protons are needed for the exact dosimetry of proton radiation. When studying the stopping power and range of protons in biological tissues, one must determine or collect data from experimentally or ICRU reports.

Heavy charged particles traversing matter lose energy primarily through the ionization and excitation of atoms. The stopping power is defined as the mean energy loss per unit path length $-dE/dx$. It depends on the charge and velocity of the projectile and, of course, the target material [6] [7].

Early investigation of the energy loss of charged particles traversing matter arrives at a general stopping power formula:

$$-\frac{dE}{dx} = \frac{4\pi e^4 N Z_2}{m_e v^2} Z_1^2 B \quad (1)$$

where: N is the target density, Z_2 is the target atomic number, m_e is the electron mass, v and Z_1 are the projectile velocity and charge respectively and B is called the "stopping number" [7].

The negative sign in Equation (1) signifies the fact that the particles lose energy as they pass through the material. For most practical purposes, the physics of the energy loss phenomena are complex, and will be not covered in detail [8].

If an ion beam penetrates through matter it loses energy due to collisions with electrons (electronic stopping) and target nuclei (nuclear stopping) [9].

Then, the total stopping power is just the sum of the stopping powers due to electronic and nuclear interactions. The nuclear component of the stopping power

can also be ignored [10].

2. Methods

The first quantum mechanical study of stopping power was done by Bethe. Bethe theory of stopping is valid when the projectile's velocity is higher than the Bohr velocity. In Bethe theory, the target is assumed as an elemental material. Bethe's treatment of the energy loss is based on the born approximation applied to the inelastic collisions between the heavy particle and the atomic electrons. In this theory, the projectile heavy particle is assumed to be structure less, and the target nucleus is assumed infinitely massive [11].

1) Calculations of electronic stopping power

The following Bethe mass stopping power equation has been used for energy range 0.04 - 200 MeV [12]:

$$-\frac{dE}{\rho dx} = \frac{5.08 \times 10^{-31} z^2 n}{\beta^2 \rho} [F(\beta) - \ln I] \quad (2)$$

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:

$$F(\beta) = \ln \frac{1.02 \times 10^6 \beta^2}{1 - \beta^2} - \beta^2 \quad (3)$$

n is calculated using the following relation:

$$n = N_a \rho \left\langle \frac{Z}{A} \right\rangle \quad (4)$$

where: N_a is 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 lung, breast and ovary are based on Bethe equation after substituting the constants from **Table 1**. In **Table 2**, the compositions of the human tissues are given.

2) Calculations of range

Range, R the range for a heavy particle is the straight distance traveled by the particle within the target. Light particles like electrons, positrons can be scattered in the path of the targets with large angles due to their low weight and it is difficult to calculate their path length. Monte Carlo methods that are based on a broad class of computational algorithms have been used in a successful manner specially for calculating the path length of light particles. On the other hand, the path length of heavy particles like protons is almost straight line. The range of protons can be calculated by some numerical integration methods. But the Continuous Slowing Down Approximation (CSDA) is a simple and common method to calculate the range of the heavy particles like protons in the targets and this method is employed in this study. Incident particles continuously lose their energy in the path of the targets and the CSDA method neglects energy loss fluctuations.

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)
Lung	1050,000	0.550	3.476×10^{29}	75.2
Breast	1020,000	0.551	3.383×10^{29}	70.3
Ovary	1050,000	0.551	3.482×10^{29}	75

Table 2. Elemental composition of Lung, Breast and Ovary tissues.

Substances	Composition
Lung	C (0.105000), N (0.031000), H (0.103000), O (0.749000), Na (0.002000), P (0.002000), S (0.003000)
Breast	C (0.332000), N (0.030000), H (0.106000), O (0.527000), Na (0.001000), P (0.001000), S (0.002000), Cl (0.001000)
Ovary	C (0.093000), N (0.024000), H (0.105000), O (0.768000), Na (0.002000), P (0.002000), S (0.002000), Cl (0.002000), K (0.002000)

The range, R for an incident proton in the CSDA method is given as:

$$R = \int_{E_0}^{E_f} \frac{dE}{MS(E)} \quad (5)$$

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 [1].

3. Results and Discussion

The results of mass stopping powers for the present tissues are given in **Table 3**. In **Figures 1-3**, the mass stopping power of tissues and their compositions are plotted and it is noted that the mass stopping power of all tissues represent the average values of its compositions. The comparison between the present calculated mass stopping powers and that of Ref. [5] are shown in **Figures 4-6**, and good agreements between two results are observed in energy range 3 - 200 MeV.

In **Table 4**, the ranges of all present human tissues are given. In **Figures 7-9**, a comparison between present results of ranges in all tissues and that of Ref. [5] are shown in energy range 0.04 - 200 MeV and good agreements are observed. In **Table 5** and **Table 6** the empirical formulae for calculating mass stopping powers and ranges for all present human tissues are given. Also percentage difference between the present results of mass stopping powers and ranges and that of Ref. [5] are calculated for all tissues and the range of differences of percentage errors are given in **Table 7**.

4. Conclusion

In this work, calculations of mass stopping power and range of protons incident on the three different human body tissues (lung, breast and ovary) have been

Table 3. Values of mass stopping power (in MeV cm²/g) of lung, breast and ovary tissues.

Proton energy (MeV)	Mass stopping power (in MeV cm ² /g)		
	Lung	Breast	Ovary
0.04	282.2618	417.5179	288.6849
0.06	722.7380	813.8908	727.9282
0.08	826.5003	895.3875	830.8763
0.1	837.7000	893.1341	841.5006
0.2	692.9473	721.1679	695.3133
0.4	483.4803	497.8423	484.8960
0.6	375.7261	358.3989	376.7606
0.8	310.2014	317.5082	311.0256
1.0	265.7808	271.6586	266.4701
2.0	160.2245	163.2136	160.6155
4.0	93.7372	95.2568	93.9559
6.0	67.7816	68.8044	67.9364
8.0	53.6391	54.4113	53.7599
10.0	44.6429	45.2639	44.7426
20.0	24.9792	25.2946	25.0335
30.0	17.6660	17.8781	17.7039
40.0	13.7764	13.9365	13.8058
50.0	11.3406	11.4692	11.3646
60.0	9.6628	9.7704	9.6832
70.0	8.4326	8.5251	8.4504
80.0	7.4896	7.5707	7.5053
90.0	6.7423	6.8145	6.7563
100.0	6.1346	6.1997	6.1474
110.0	5.6301	5.6895	5.6419
120.0	5.2043	5.2588	5.2151
130.0	4.8397	4.8901	4.8498
140.0	4.5239	4.5707	4.5333
150.0	4.2475	4.2912	4.2563
160.0	4.0034	4.0445	4.0117
170.0	3.7863	3.8249	3.7941
180.0	3.5917	3.6282	3.5991
190.0	3.4163	3.4510	3.4234
200.0	3.2574	3.2903	3.2641

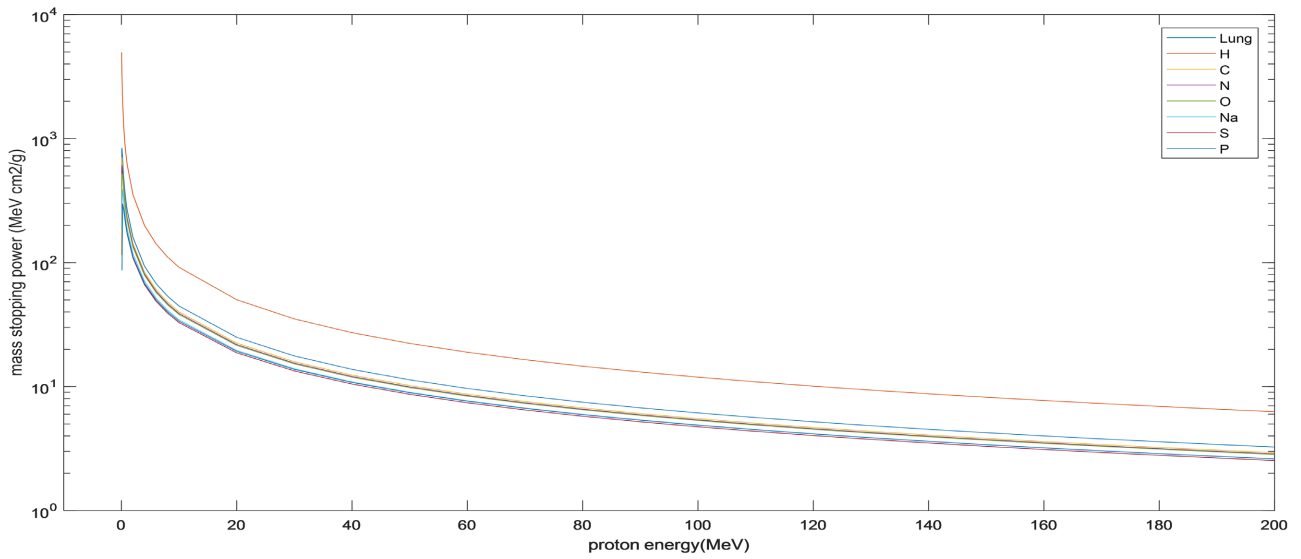


Figure 1. Mass stopping power of Lung and its composition.

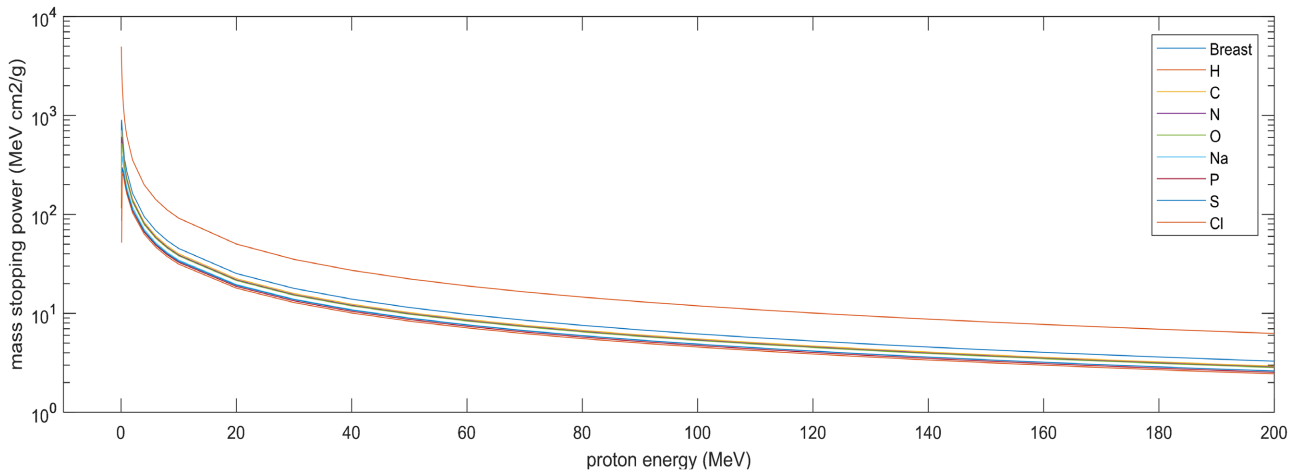


Figure 2. Mass stopping power of Breast and its composition.

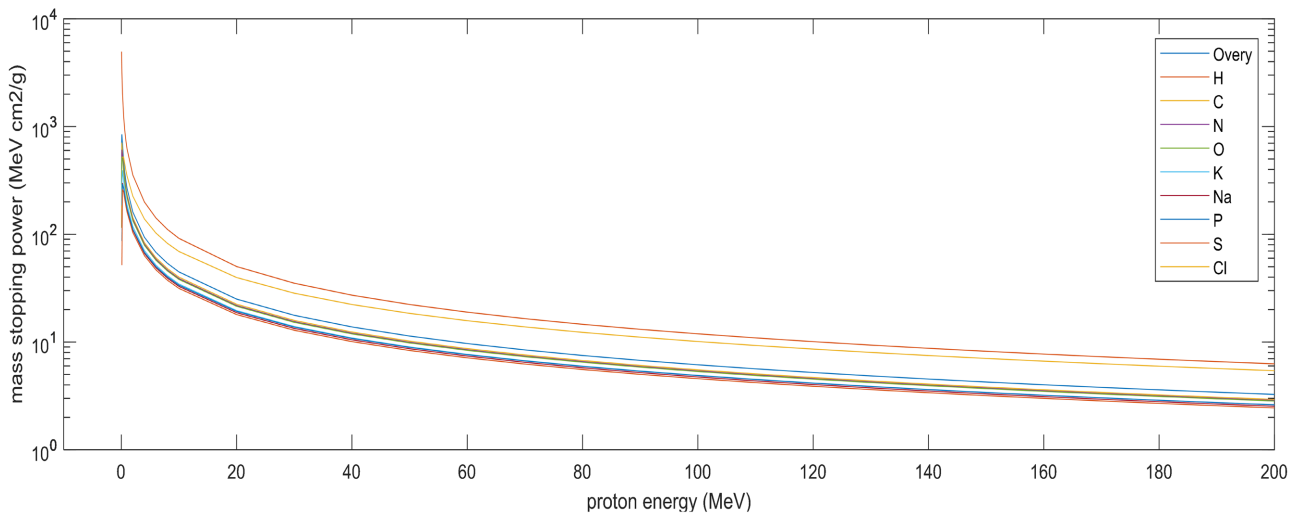


Figure 3. Mass stopping power of ovary and its composition.

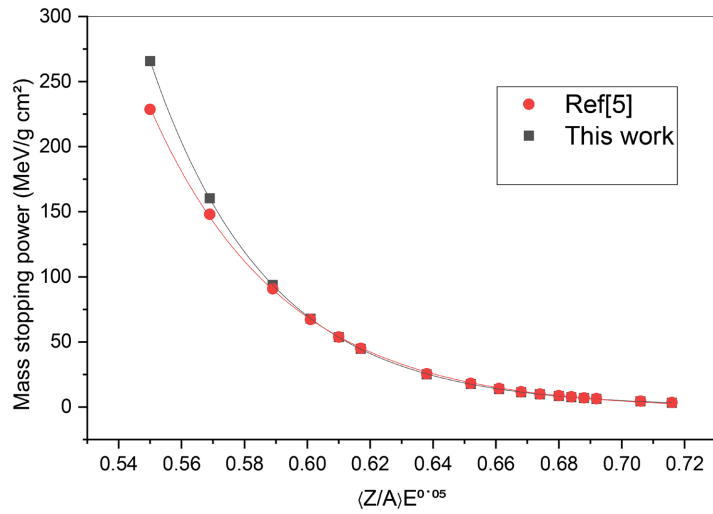


Figure 4. Mass stopping power of Lung versus $\langle \frac{Z}{A} \rangle E^{0.05}$.

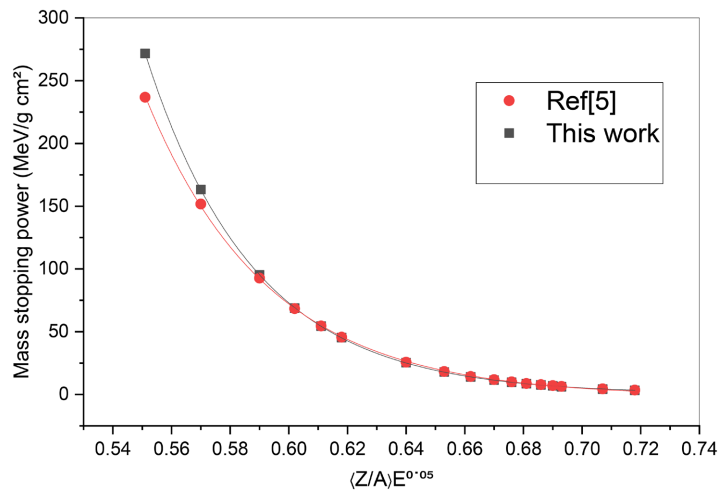


Figure 5. Mass stopping power of Breast versus $\langle \frac{Z}{A} \rangle E^{0.05}$.

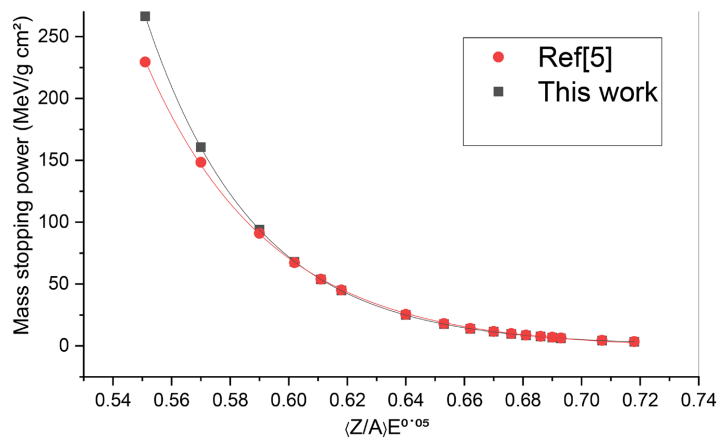


Figure 6. Mass stopping power of Overy versus $\langle \frac{Z}{A} \rangle E^{0.05}$.

Table 4. Values of range (in g/cm²) of lung, breast and ovary.

Proton energy (MeV)	Range (g/cm ²)		
	Lung	Breast	Ovary
0.04	1.512×10^{-5}	1.345×10^{-5}	1.499×10^{-5}
0.06	3.008×10^{-5}	2.692×10^{-5}	2.983×10^{-5}
0.08	4.900×10^{-5}	4.403×10^{-5}	4.860×10^{-5}
0.1	7.154×10^{-5}	6.449×10^{-5}	7.098×10^{-5}
0.2	2.318×10^{-4}	2.109×10^{-4}	2.301×10^{-4}
0.4	7.510×10^{-4}	6.902×10^{-4}	7.462×10^{-4}
0.6	0.0015	0.0014	0.0015
0.8	0.0024	0.0023	0.0024
1.0	0.0036	0.0033	0.0035
2.0	0.0115	0.0108	0.0115
4.0	0.0373	0.035	0.0371
6.0	0.0742	0.070	0.0739
8.0	0.120	0.115	0.120
10.0	0.176	0.169	0.175
20.0	0.571	0.555	0.570
30.0	1.137	1.110	1.134
40.0	1.852	1.815	1.848
50.0	2.704	2.659	2.699
60.0	3.684	3.631	3.678
70.0	4.784	4.727	4.778
80.0	6.001	5.939	5.994
90.0	7.327	7.265	7.320
100.0	8.761	8.699	8.753
110.0	10.298	10.239	10.290
120.0	11.936	11.882	11.927
130.0	13.671	13.625	13.662
140.0	15.502	15.465	15.493
150.0	17.427	17.402	17.418
160.0	19.442	19.433	19.434
170.0	21.548	21.555	21.540
180.0	23.741	23.769	23.734
190.0	26.021	26.071	26.014
200.0	28.386	28.461	28.380

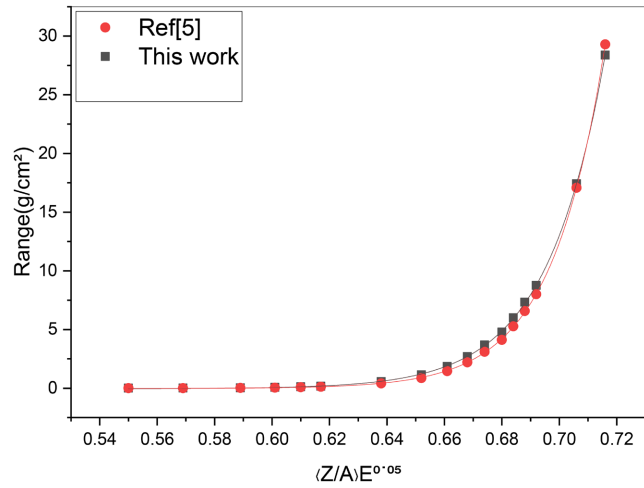


Figure 7. Range of Lung versus $\left(\frac{Z}{A}\right)E^{0.05}$.

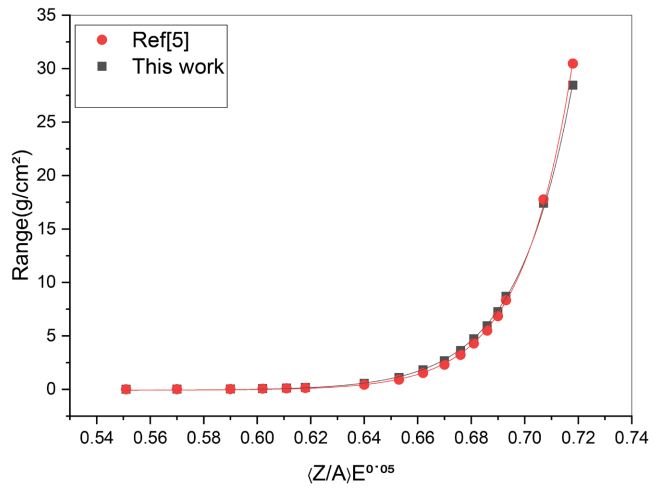


Figure 8. Range of Breast versus $\left(\frac{Z}{A}\right)E^{0.05}$.

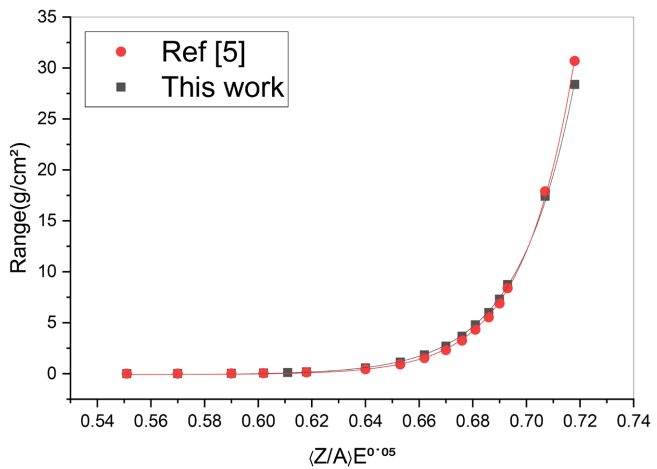


Figure 9. Range of Ovary versus $\left(\frac{Z}{A}\right)E^{0.05}$.

Table 5. The empirical formulae for calculating mass stopping powers.

Substances	The empirical formulae for calculating mass stopping powers	
	$y = A_1 e^{x/t_1} + y_0$	
	This work	Ref. [5]
Lung	$A_1 = 6.4723 \times 10^8, t_1 = -0.0374$ $y_0 = 0.10311$ $R^2 = 0.99999$	$A_1 = 1.0140 \times 10^8, t_1 = -0.04235$ $y_0 = -2.17377$ $R^2 = 0.99982$
Breast	$A_1 = 7.424 \times 10^8, t_1 = -0.03717$ $y_0 = 0.33231$ $R^2 = 0.99999$	$A_1 = 1.3298 \times 10^8, t_1 = -0.04166$ $y_0 = -1.74685$ $R^2 = 0.99988$
Ovary	$A_1 = 6.7234 \times 10^8, t_1 = -0.0374$ $y_0 = 0.25388$ $R^2 = 1$	$A_1 = 1.05463 \times 10^8, t_1 = -0.0423$ $y_0 = -1.998$ $R^2 = 0.99984$

Table 6. The empirical formulae for calculating range.

Substances	The empirical formulae for calculating range	
	$y = A_1 e^{x/t_1} + y_0$	
	This work	Ref. [5]
Lung	$A_1 = 2.0524 \times 10^{-14}, t_1 = 0.02054$ $y_0 = -0.04347$ $R^2 = 0.99999$	$A_1 = 5.6893 \times 10^{-16}, t_1 = 0.01861$ $y_0 = -0.0191$ $R^2 = 0.99992$
Breast	$A_1 = 3.1976 \times 10^{-14}, t_1 = 0.02058$ $y_0 = -0.09494$ $R^2 = 1$	$A_1 = 1.5038 \times 10^{-15}, t_1 = 0.01912$ $y_0 = -0.08055$ $R^2 = 0.99988$
Ovary	$A_1 = 4.1072 \times 10^{-14}, t_1 = 0.02102$ $y_0 = -0.09538$ $R^2 = 1$	$A_1 = 1.5704 \times 10^{-15}, t_1 = 0.01914$ $y_0 = -0.08739$ $R^2 = 0.99984$

Table 7. Percentage difference between present result and that of Ref. [5].

Tissue	Range of percentage difference between present result and Ref. [5] of mass stopping power	Range of percentage difference between present result and Ref. [5] of range
Breast	-6.07% - 12.82%	-7.06% - 21.29%
Lung	-6.46% - 13.95%	-3.20% - 26.95%
Ovary	-6.44% - 13.91%	-8.13% - 23.47%

done and the following conclusions are drawn:

- 1) The mass stopping power of each tissue gives the average value of mass stopping power of its compositions in energy range of 0.04 - 200 MeV;
- 2) It is also noted that the empirical formulae for both mass stopping power and range for each human tissue studied in the present work are simple and widely applicable;

3) Values for mass stopping power and ranges of protons for breast, lung and ovary tissues are in good agreement with the data proposed by other researchers. This comparison is very important in terms of reliability of present work;

4) It also observed that the maximum value of mass stopping power was at 0.1 MeV and after that, the mass stopping power started to decrease with increasing energy;

5) The empirical formulae suggested for mass stopping power and ranges of protons are simple and they covered a large range of proton energy (1 - 200 MeV) as well as gave important information for those interesting 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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