E-ISSN 2656-8039

INTERNATIONAL JOURNAL OF ENVIRONMENT, ENGINEERING & EDUCATION

www.ijeedu.com

Vol. 3, No. 3, 2021

Research Article

Stopping Power and Range for Proton Interaction with Lymph Tissues

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Received: *July 29, 2021;* ***Accepted:*** *September 15, 2021;* ***Published:*** *December 25, 2021*

Abstract: In this paper, we calculated the mass stopping power (in MeV cm2/g) and the range (cm) of proton in one of the types of body tissues (lymph), from 1 Kev to 200 MeV energy range. They are using the Bethe and Ziegler equations, SRIM program (version 2013) and Ziegler (Vol. 3) data by considering the tissue composed of several elements, so the atomic number (Z) and atomic weight (A) for the component in the tissue are meaning. The calculation results show that the Ziegler equation gives better results than using the Bethe equation. However, in terms of the loss of proton energy in the tissue, the four methods used are approximately the same.

Keywords: Bethe Equation, Proton Therapy, Stopping Power, SRIM Program, Ziegler Equation.

1. Introduction

Nuclear science has contributed significantly to tumor therapy with heavy charged particles [1]. Radiation therapy uses the radiobiological effects of ionizing radiation (charged particles, neutrons, gamma rays or x-rays) to destroy tumor cells. The success of radiotherapy depends on the ability of the therapy system to concentrate the quantity (dose) of radiation on the target region (tumor). Ideally, a lethal while minimizing the irradiation of adjacent healthy tissues [2]. The biological effect of ionizing radiation on human beings depends on the absorbed dose, type of radiation energy, and organs irradiated [3]. Information on stopping power is essential in many fields involving radiation. Their accuracy may critically affect calculations, measurements, and interpretation of experiments [4]. Protons have a necessary effect in radiation therapy as they can deliver their energies to the target, and is no radiation beyond the range end. The total stopping power for proton interacting with each element or chemical composition (in the lymph tissue) are calculated by the Bethe formula [5]; it is the preferred method of evaluating the stopping power at sufficiently high energies (above 1MeV for protons). This theory contains a key parameter, (I) the mean excitation energy of the stopping medium flowing [6].

1.1. Beth Equation

The Bethe formula or Bethe-Bloch formula [7], the mean energy loss per distance travelled of swift charged particles (protons, alpha particles, atomic ions) traversing matter (or the stopping power of the material).

$$\frac{dE}{dx}\left(\frac{Mev}{10^{21}atom/cm^2}\right) = 0.239114\frac{Zt}{Ep}ln[\,2.17\times10^{-3}\frac{Ep}{IeV}] \qquad (1)$$

dE/dx = stopping power.
Zt = atomic number of the target.
(I) = the mean excitation energy of the target.
E_p= Energy of the proton.

$$I(eV) = 9.76 + 58.8\ \times Z^{-1.19})Z \qquad (2)$$

This Article Citation: *S. M. Hadi, "Stopping Power and Range for Proton Interaction with Lymph Tissues," Int. J. Environ. Eng. Educ., vol. 3, no. 3, pp. 28-32, 2021.*

The results of this formula are valid for energies > 1 MeV, where more consistent results are recorded. Good agreements with the results of SRIM and PSTAR are observed [8].

1.2. Ziegler Formula

To bridge the gap between the high- and low-energy theories, interpolation formulas of different levels of complexity were proposed by Varelas and Biersack [9], [10]:

Where (s) is the stopping power, is calculated as:

$$S = \frac{S_{low}\, S_{High}}{S_{low} + S_{High}} \qquad (3)$$

Where S $_{Low}$ (Low Energy Stopping)
And S $_{High}$ (High Energy Stopping)

$$Stopping\ = A_1 E^{1/2} \qquad \text{From (1-10 HeV)} \qquad (4)$$

From (10-999 KeV):

$$(Stopping)^{-1}\ =\ (S_{Low})^{-1}\ +\ (S_{High})^{-1} \qquad (5)$$

Where:

$$S_{Low} = A_2 E^{0.45} \qquad (6)$$

$$S_{High} = \left(\frac{A_3}{E}\right) In \left[1 + \left(\frac{A_4}{E}\right) + (A_5 E)\right] \qquad (7)$$

From (1000 KeV-100000 KeV):

$$Stopping = \left(\frac{A_6}{\beta^2}\right) \ln\left[\left(\frac{A_7\beta^2}{1-\beta^2}\right) - \beta^2\ - \sum_{i=0}^{4} A_{i=8}(\ln E)^i\right]$$

$$\text{in} \quad \frac{eV}{(10^{15} atoms/cm^2\ )} \qquad (8)$$

Here A1... Ai, are fitting constants represented in the reference [5].

1.3. Stopping and Range of Ions in Matter (SRIM)

SRIM is a group of programs that calculate the stopping and range of ions (up to 2 GeV/AMU) into matter using a quantum mechanical treatment of ion-atom collisions (assuming a moving atom as an "ion", and all target atoms as "atoms"). This calculation is very efficient using statistical algorithms that allow the ion to make jumps between calculated collisions and then average the collision results over the intervening gap. The ion and atom have a screened Coulomb collision during the clashes, including exchange and correlation interactions between the overlapping electron shells. The ion has long-range interactions creating electron excitations and plasmons within the target. These are described by including a description of the target's collective electronic structure and interatomic bond structure when the calculation is set up (tables of nominal values are supplied). The charge state of the ion within the target is described using the concept of effective charge, which includes a velocity-dependent charge state and long-range screening due to the collective electron sea of the target [11].

1.4. Energy Loss in Compound and Mixture

When passing through matter, the fast charged particles ionize the molecule or atom they encounter; therefore, fast particles lose energy gradually in many small steps. Stopping power means the average energy loss of the particle per unit path length [9]. We have calculated the stopping power for each element in the tissue, then by a linear combination of the constituent stopping powers (Bragg's additivity rule) found the total stopping power, as:

$$\frac{S}{\rho} = \sum_i wi\ (\frac{S}{\rho})_i \qquad (9)$$

Where *wi* is the fraction by weight, and
$(\frac{S}{\rho})_i$ Is the mass stopping power of the *j* constituent [12].

1.5. Range

The range is the distance travelled by the proton before stopping. The field with energy (E0) is calculated by integrating stopping power to zero point [13].

$$R(E_0) = \int_o^{E_o} (-\,dE/dx)^{-1} dE \qquad (10)$$

Particles such as protons and neutrons with specific energies will lose all their powers in an actual distance in a medium, which is called the range [14].

2. Data Reduction and Analysis

The stopping power depends on the type and the energy of the particle and the properties of the material it passes [9]. The mass stopping power is valuable because it expresses the charged particle's energy loss rate per g—cm-2 of the traversed medium. The mass stopping power is linear (MeV/cm) divided by density [12].

The energy transferred to tissue by protons is inversely proportional to the proton velocity as protons lose their power mainly in electromagnetic interactions with orbital electrons of atoms. The more the protons slow down, the higher the energy they transfer to tissue per track length, causing the maximum dose deposition at a certain depth in tissue [15].

Chemical compositions of human tissues are essential in studying micro-dosimetry distributions in humans irradiated with radiation one may represent human tissues by their atomic compositions (% wt by elements). Chemical compositions of human tissues generally depend on breed, diet, age, sex, health, and they may vary appreciably (5-10%) among individual human beings [16].

Each tissue consists of elements. Proton interacts with them; therefore, the knowledge of the ratios of these elements is essential to calculate the mass stopping power for protons in the tissues and the density of the tissue. These percentages and tissue density values are given in Table 1.

Table 1. Elemental composition of lymph tissue and density of the tissue [17].

Human Tissue	Density	Composition (element: fraction) by weight
Lymph tissue	(Kg m-3)	H: 10.8
		C: 0.04 1
		N: 0.011
		O: 0.832
		Na: 0.003
		S: 0.001
		Cl: 0.004

After that, and according to Equation 2, found the Ionization potential for any element in the tissue as shown in Table 2.

Table 2. Ionization potential and atomic numbers of elements considered for lymph tissue.

No.	Elements	Atomic Number	Ionization Potential (MeV)
1	Hydrogen (H)	1	6.8560×10^{-5}
2	Carbon (C)	6	1.0039×10^{-4}
3	Nitrogen (N)	7	1.0895×10^{-4}
4	Oxygen (O)	8	1.1769×10^{-4}
5	Sodium (Na)	11	1.4464×10^{-4}
6	Sulphur (S)	16	1.9088×10^{-4}
7	Chlorine (Cl)	17	2.0024×10^{-4}

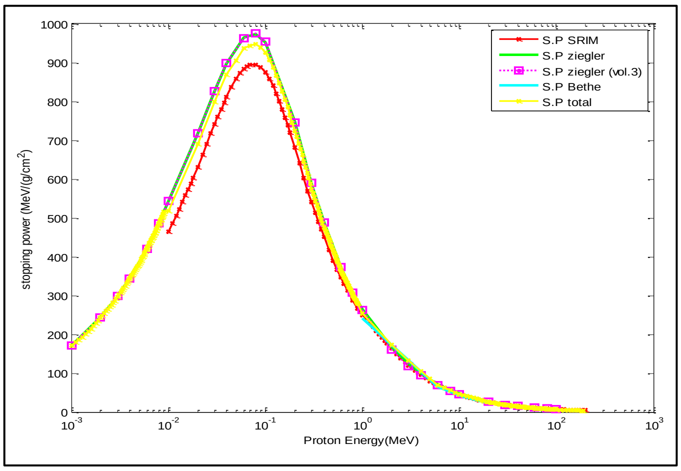

Figure 1. Stopping Power for Lymph Tissue (Present Work).

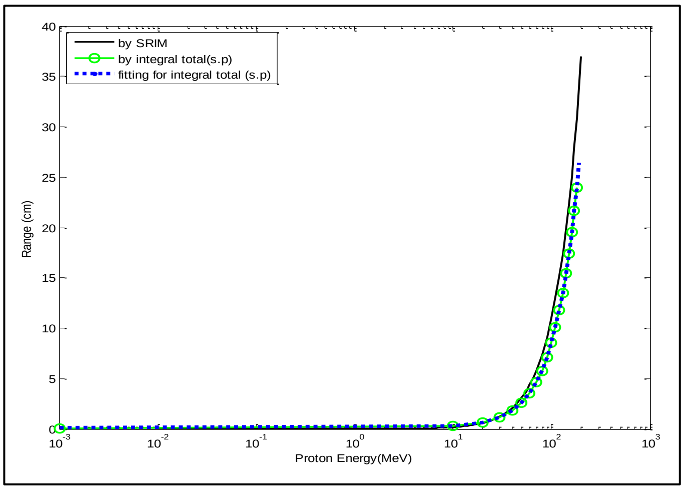

Figure 2. Range of Proton in Lymph Tissue

3. Result and Discussions

The mass stopping power values for proton in lymph tissue calculated in units (MeV-cm2/g) in the energy range (1 KeV-200MeV) using the above methods show Compatible with the low and high energy region different at median energy range. As shown in Figure 1, At high energy (>1MeV), stopping power decrease with increased photon energy, i.e., does not have enough time to collide, and at intermediate energy region, stopping power reaches the maximum value (more ionization and excitation). In contrast, at low energies (E <25KeV), we observe the increase of the stopping power with the rise of the proton's energy.

Figure 2 shows the proton range in (cm) and the energy range (1 KeV-200MeV) and is consistent with the experimental formula curve the proton range in the tissue is increased by increasing its energy. At energy (0.08 MeV), the proton reaches maximum energy loss in the tissue, where stopping power is (947.9906 MeV-cm2/g) and the range of the proton in that case (0.08MeV) is ~ (0.0135 cm), i.e., the tumor in this range requires the energy of the proton is ~ (0.0135 MeV) to destroy it in the tissue. The percentage deviation between the experimental and the calculated stopping power values (using the above methods) for lymph tissue are shown in Table 3.

Table 3. Percentage Deviation (Stopping Power) in Lymph Tissue (MeV-cm^2/g)

E_P (MeV)	Lymph Tissue								S.P (P.W)
	Stopping Power								
	Bethe	Error	Ziegler	Error	Ziegler (Vol. 3)	Error	SRIM	Error	
0.001	-	-	171.9211	-0.0568	171.7256	0.0570	-	-	171.8234
1	241.0115	5.6478	264.4091	-3.7010	262.6737	-3.0648	250.3918	1.6900	254.6233
2	205.5936	-15.3096	167.1687	4.1571	159.7417	8.9997	163.9561	6.1979	174.1180
3	170.1757	**-21.8434**	123.4268	**7.7590**	117.9102	**12.8007**	120.4963	**10.3797**	133.0035
4	134.7579	-21.2042	98.9881	7.2690	94.6882	12.1402	96.2983	10.2652	106.1835
5	99.3400	-12.5447	85.5063	1.6043	81.8782	6.1065	80.7867	7.5401	86.8781
6	63.9526	7.4841	72.0306	-4.5699	69.0740	-0.4851	69.8978	-1.6580	68.7389
7	59.0160	4.8282	64.6296	-4.2770	62.0203	-0.2498	61.7956	0.1130	61.8654
8	54.0794	2.5313	57.2314	-3.1156	54.9692	0.8716	55.5131	-0.1167	55.4483
9	49.1428	3.0737	52.5000	-3.5175	50.4765	0.3503	50.4938	0.3159	50.6533
10	44.2061	4.2444	47.7713	-3.5354	45.9863	0.2090	46.3658	-0.6112	46.0824
15	30.9479	11.2896	37.3580	**-7.8061**	36.1010	-4.5960	33.3603	3.2419	34.4418
20	24.1930	7.1831	26.9426	-3.7554	26.2137	-1.0792	26.3740	-1.6804	25.9308
25	20.0058	9.4283	23.0407	-4.9855	22.5364	-2.8594	21.9851	-0.4235	21.8920
30	17.1285	8.1297	19.1389	-3.2285	18.8590	-1.7922	18.9574	-2.3020	18.5210
35	15.0183	9.3899	17.0574	-3.6870	16.9151	-2.8767	16.7231	-1.7616	16.4285
40	13.3989	8.8933	14.9760	-2.5741	14.9713	-2.5435	15.0160	-2.8336	14.5905
45	12.1136	10.5906	13.8735	-3.4382	13.9381	-3.8858	13.6608	-1.9347	13.3965
50	11.0668	11.3809	12.7709	-3.4814	12.9048	-4.4828	12.5626	-1.8810	12.3263
60	9.4608	10.2867	10.5659	-1.2484	10.8384	-3.7312	10.8708	-4.0181	10.4340
70	8.2828	11.8752	9.4004	-1.4255	9.7466	-4.9268	9.6357	-3.8326	9.2664
80	7.3793	11.6678	8.2349	0.0656	8.6549	-4.7903	8.6922	-5.1989	8.2403
90	6.6629	12.9208	7.5088	0.1998	7.9762	-5.6719	7.9471	-5.3265	7.5238
100	6.0801	10.3798	6.7826	-1.0527	7.2976	**-8.0355**	7.3423	-8.5954	6.7112
150	4.2680	**14.2127**	-	-	-	-	5.4812	**-11.0669**	4.8746
200	-	-	-	-	-	-	4.5195	-	-

Table 3 maximum deviation as shown the 'red' color, and minimum 'green' color, where deviation decreases as the energy of the proton increases (except Bethe). So, Table 3 leads that Ziegler gives better results from other methods.

4. Conclusion

Calculating the loss of proton energy in the tissue at high accuracy is necessary for the radiation treatment of cancer, and the four methods give approximately the same results. We conclude from the results that we can propose an empirical equation for the range of the proton in the tissue:

$$F(x) = a \times x^{b+c} \tag{11}$$

Where **a** and **b** and **c** are fitting constant

(a= 0.0002368, b=1.775, c= 0.01352);

F(x) = range of proton in the tissue;

X = energy loss of proton Ep and the equation in lymph tissue become:

$$F(x) = 0.0002368 \times E_p{}^{1.775+0.01352}$$

The error rate in these equations is 1.

Acknowledgments

Thanks to the Iraqi Ministry of Education for its support and those who helped to complete this research.

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