DOI: 10.24996/ijs.2021.62.9(SI).10

ISSN: 0067-2904

Theoretical Study for the Calculation of Proton Range in Human Body Tissues

Shaima M. Hadi[1]*, Bashair M. Saied[2]

[1]Iraqi Ministry of Education, Rusafa third, Baghdad, Iraq

[2]Physics Department, Ibn Al-Haytham College of Education and Pure Sciences,, Baghdad University, Baghdad, Iraq

---

Received: 2/9/2020 Accepted: 14/3/2021

Abstract

The main rationale for using charged particles in radiation therapy is the strong rise of energy loss (deposited dose) with maximum penetration depth (Bragg peak) and rapid dose deposited behind the peak. Thus, a large dose can be applied to a deep seated tumor, with saving the surrounding normal tissues . Proton radiotherapy is nowadays an established method in the management of cancer diseases, although its availability is still limited to a few specialized centers. In this study, the range and the stopping power for proton interaction in the skeleton and intestine tissues, for an energy range from 0.01 to 300 MeV, was studied. The numerical calculations and analyses of Bethe Ziegler, along with CASP and SRIM software programs, were applied using Matlab program. The absorbed dose and the Bragg peak were calculated and presented as tables and figures .

Keywords:_ Range, Bethe equation, Ziegler equation ,energy loss, Bragg peak, Absorbed dose.

دراسة نظرية لحساب مدى البروتون في انسجة جسم الانسان

شيماء محسن هادي[1], بشائر محمد سعيد[2]

[1] وزارة التربية العراقية، مديرية تربية الرصافة الثالثة، بغداد, العراق

[2] قسم الفيزياء، كلية التربية للعلوم الصرفة ابن الهيثم، جامعة بغداد، بغداد، العراق

الخلاصة

الأساس المنطقي الرئيسي لاستخدام الجسيمات المشحونة في العلاج الإشعاعي هو ارتفاع مقدار الطاقة المفقودة بزيادة عمق الاختراق وصولا الى اقصى قيمة (Bragg peak) ثم يحدث هبوط في الجرعة خلف هذه القمة. لذلك يمكن تطبيق جرعة كبيرة على ورم عميق الجذور، في حين تجنيب الأنسجة السليمة المحيطة بها. العلاج الإشعاعي بالبروتونات في الوقت الحاضر هو طريقة راسخة في إدارة معالجة امراض السرطان , على الرغم من توافرها لا تزال تقتصر على عدد قليل من المراكز المتخصصة. في هذه الدراسة تم دراسة قدرة الايقاف والمدى لتفاعل البروتون مع الهيكل العظمي والأمعاء من جسم الانسان بمدى طاقة تتراوح بين (0.01-300 MeV). الحسابات العددية والتحليلات لمعادلات , (Ziegler) و (Bethe) ، وبرنامج (SRIM) و (Casp) تمت باستخدام برنامج Matlab. ان الجرعة الممتصة وو (Bragg peak) تم حسابها وعرضها كجداول واشكال

---

*Email:Shaima-shaima.mo2015@gmail.com

Introduction

Protons have more different dosimetric characteristics than photons used in conventional radiation therapy [1]. High energy protons enter the body, depositing a lower amount of radiation dose at the body surface, whereas the higher dose, i.e. at the end of the range, is deposited deep in tissues (called the Bragg peak) [2]. Protons moving through substances slow down, loosing energy in nuclear or atomic interaction events. This leads to a reduction in the energy of the proton and, consequently, increased interactions with orbiting electrons. At the end of the proton bath, the maximum interaction with electrons occurs, causing maximum energy release within the targeted area [1].The biological effects of ionizing radiation on human beings depend on the type of radiation, absorbed dose and irradiated organs [3]. The physical properties of protons result in advantages of protons treatment over conventional radiation, because the region of maximum energy deposition can be positioned within the area for each beam direction. This leads to a highly conformal high dose region. Proton therapy is of particular attention for tumors located close to serially organized tissues, such as most tumors that are close to the spinal cord. It is still in general a small, although increased, number of radiotherapy patients who have been treated with protons, due to the cost of the proton facility and other reasons [1] . The goal of this work is to calculate the range of protons and stopping power with these tissues because of their importance in radiation biology.

Theory: Stopping power (-dE/dx) is defined as the energy lost by protons per unit path length. In this work, the mass stopping power concept [$\frac{1}{\rho}(-dE/dx)$] is adopted and this amount is not the density dependent (ρ) of the material [4].

$$(-dE/dx)_{\text{compound}} = \sum_i wi(dE/dx)_i \quad \text{...(1).}$$

where wi is the fraction by weight and $(dE/dx)_i$ is the mass stopping power of the constituent .

The calculations for Beth formula and Ziegler formula, as well as SRIM and Casp programs, were performed as follows.

- Beth formula for a proton particle is given by [5]:

$$-dE/dx = \frac{4\pi n z^2 k_o^2 e^4}{m_o V^2}\ln\left(\frac{2m_o V^2}{I}\right) \quad \text{...(2)}$$

where

z= charge of incoming particle.

n= number of electrons per unit volume in the stopping material.

m_o= rest mass of the electron.

V= velocity of the particle.

e= electron charge.

$K_o = 1/4\pi\varepsilon_o$.

I= mean excitation energy of the medium.

- The stopping power was determined using Ziegler's equation for low and high energies. The parameters of the elements were also mentioned in an earlier study [6].

- Calculations of the stopping power for a proton in each element of tissues were presented with the SRIM code, which is an acronym for Stopping and Range of an Ion in a Matter. Ziegler *et al.*'s SRIM software is probably the most widely used computer program to predict stopping powers of ions in a matter. The moving atom is conventionally considered as an ion (whether it is charged or neutral) and the target is an atom. The software simulates the scattering and slowing down of an energetic ion through interactions with the target atoms. The collision cascade simulation is achieved by following the ions which, after penetration into the target, suffer multiple nuclear and electronic collisions [7].

- CasP is an acronym for Convolution approximation for swift Particle. Unitary convolution approximation provides an impact parameter-dependent version of the quintal perturbation theory. The impact parameter in a collision denotes the perpendicular distance between the incoming projectile trajectory and the target nucleus (initially at rest) [8].

Range is an experimental concept of the charged particle that expresses the thickness of the absorption material that the charged particle can penetrate. It depends on the kinetic energy of the particle mass, the_charge of the particle, and the configure of the absorbent medium. The range is expressed by the following equation :

$$R = \int_{0}^{E} -[dE/dx]^{-1}\, dE \text{ ....(3)}$$

The range is actually an average value because scattering is a statistical process . The spread will be smaller for heavier particles. These properties have implications for the use of radiation in therapeutic situations [9].

Absorbed dose is an absorption of the energy deposited in the tissues as a result of ionizing radiation falling on them [10]. It represents the energy deposited by protons per gram of the material. The conventional unit for the absorbed dose is the Rad (radiation absorbed dose), and is equivalent to the absorption of (100) erg of energy in (1) g of absorbing medium, which is written typically for the tissues as:

[1 rad = 100 erg/g]

The SI unit of absorbed dose is the gray (Gy) and is defined as the absorption of 1 Joule of energy per kilogram of material [11]:

1Gy= 1 J/kg

The absorbed dose is used to estimate the potential of biochemical changes in many tissues [10]:

$$\text{Absorbed dose(rad)} = \frac{E}{1g}\,\frac{1.6*10^{\wedge}-18}{1Mev}\,\frac{J10^{\wedge}7erg}{1J}\,\frac{1rad}{100erg/g}\ .$$

Results and Discussion

In the present work, Beth formula, Zeigler's formula, and SRIM and Casp programs were used for the calculations of the mass stopping power of human (skeleton and intestine) tissues for protons with an energy interval of 0.01- 300 MeV. Each tissue consists of elements, the ratios of which are important to calculate the mass stopping power for protons in the tissues. Therefore, the chemical compositions of the skeleton and intestine tissues are given in Table-1.

Table 1-The chemical composition of skeleton and intestine tissues, with fractional weight and ionization potential of the elements

Human Tissue	**Composition (element: fraction) by weight**										
	H	**C**	**N**	**O**	**Na**	**Mg**	**P**	**S**	**Cl**	**K**	**Ca**
skeleton	0.063	0.261	0.039	0.436	0.001	0.001	0.061	0.003	0.001	0.001	0.133
intestine	0.106	0.115	0.022	0.751	0.001	-	0.001	0.001	0.002	0.001	-
Ionization potential $\times10^{-4}$(MeV)	68.56	1.0039	1.0895	1.1769	1.4464	1.5379	1.8155	1.9088	2.0024	2.1905	2.2848
Mass atomic number	1.0079	12.0107	14.0067	15.9994	22.9897	24.3050	30.9737	32.065	35.453	39.0983	40.078

The following figures illustrate the measurements in this work.

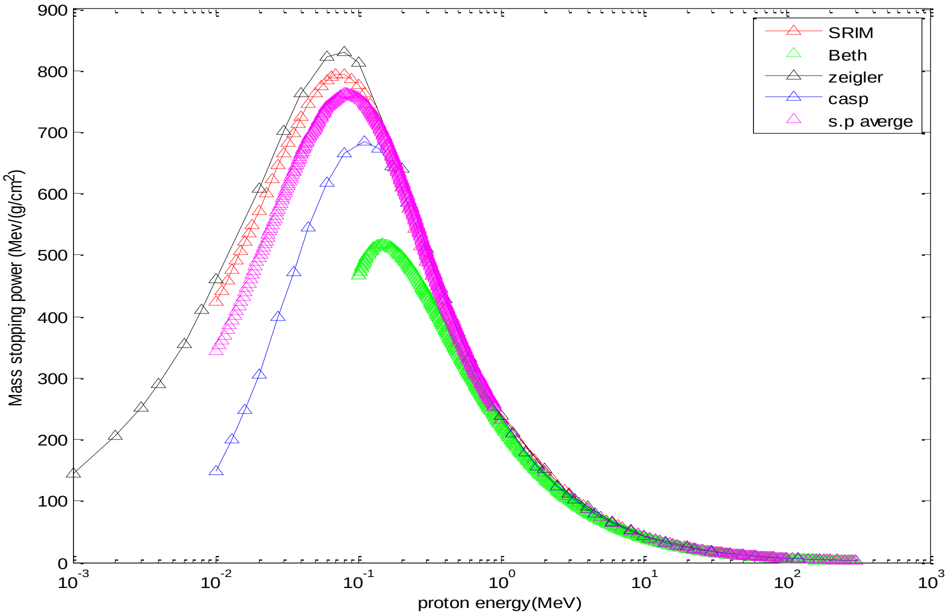

Figure 1-Mass stopping power for proton in the human skeleton tissue.

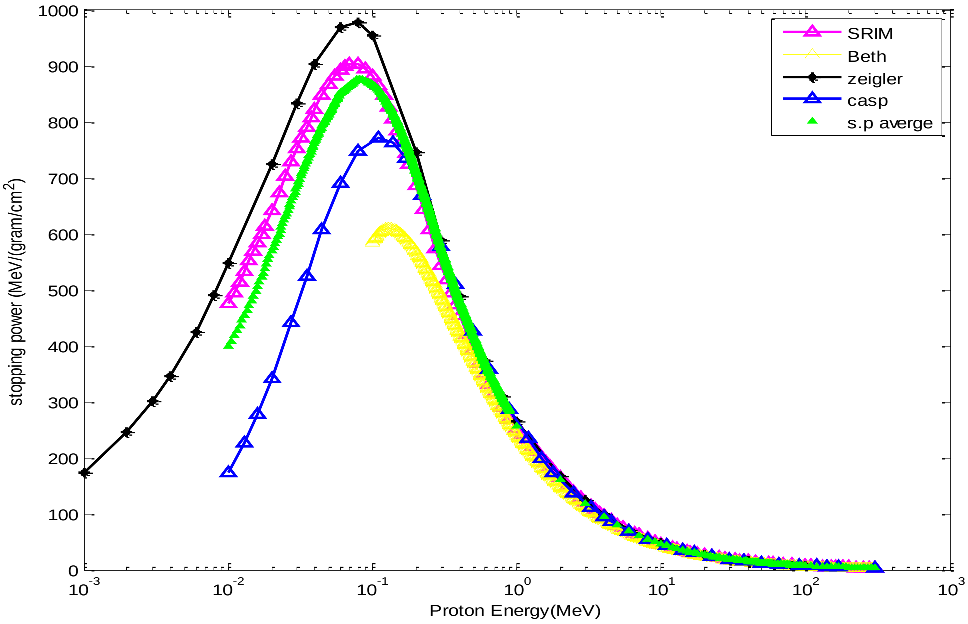

Figure 2- Mass stopping power for proton in the human intestine tissue.

By using eq.(3), the relationship with total mass stopping power shows Bragg peak for proton in each tissue, as in the following figures.

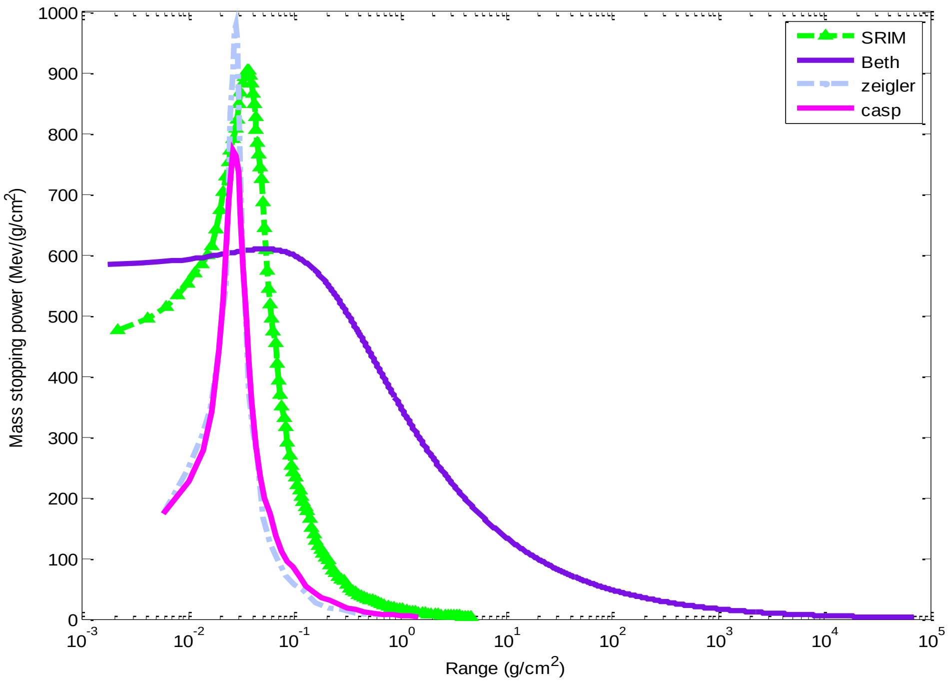

Figure 3-Bragg peak for proton in the human skeleton tissue.

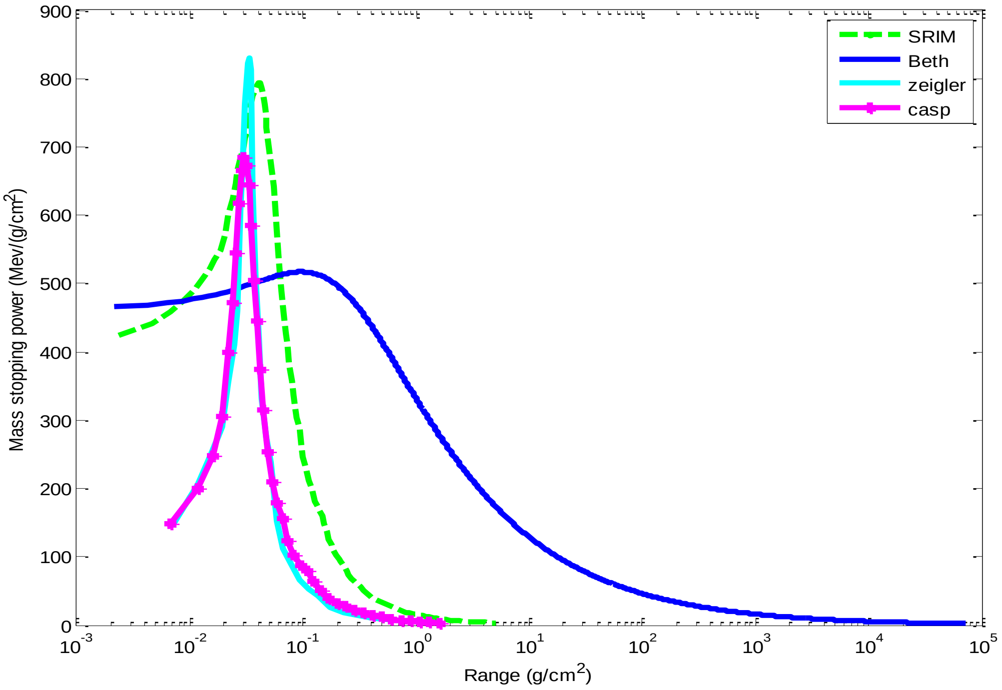

Figure 4- Bragg peak for proton in the human intestine tissue.

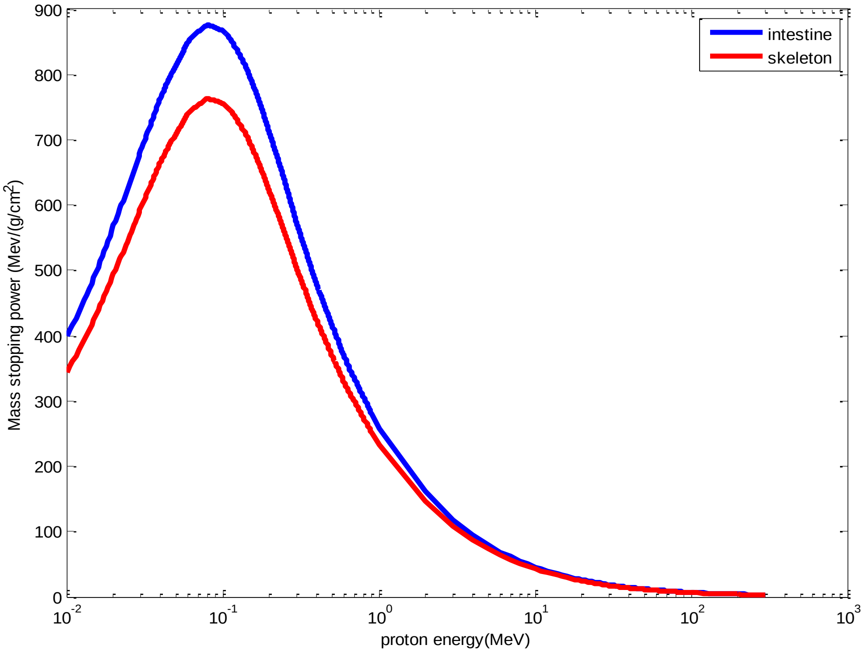

Figure 5- Total mass stopping power of proton in human intestine and skeleton tissues**.**

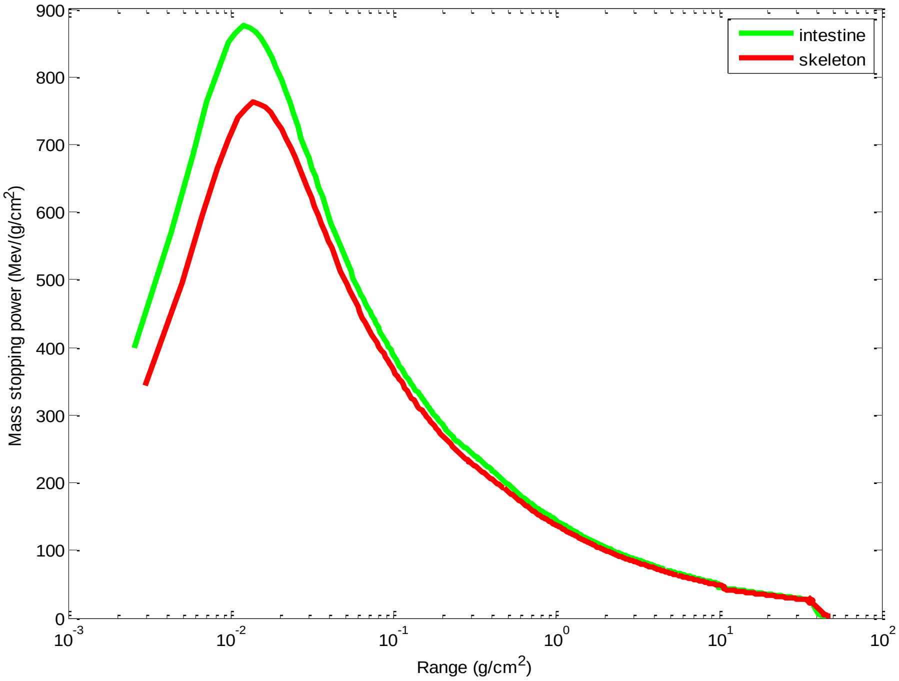

Figure 6- Bragg peak of human skeleton and intestine tissues.

In addition, proton ranges in these tissues were calculated using the language of the Matlab , as shown in Figure-7.

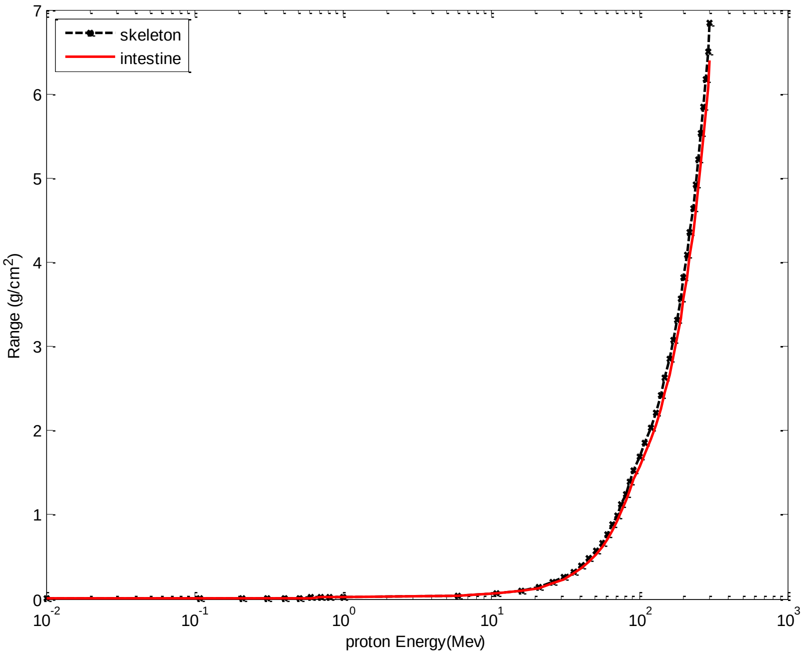

Figure 7-Range of proton in human skeleton and intestine tissues.

Figures-(1, 2) show mass stopping power, calculated by four methods, in each tissue irradiated by protons. Similarities in the stopping power behaviors in the four methods comes from the fact that the stopping power depends on the energy and its maxima values occur at energies located in 0.05–0.5 MeV. For all methods used, the stopping power increases rapidly at low energies up to the maximum, as shown in the Ziegler formula, SRIM program and Casp program. While at high energies, the stopping power gradually decreases with increasing the energy because the protons have high velocity and the possibility of an interaction with the electrons decreases and, _hence, the energy loss decreases. The maximum loss of the proton energy in the intestine tissue is greater than that in the skeleton tissue for the same range of energy, although the components of the intestines are lower (in weight; see Table- 1) than those in the skeleton due to the high percentage of hydrogen in the intestine tissue, which is responsible for the loss of energy significantly within the tissue. The Bragg peak related to the stopping power (Figure- 6) of the intestinal tissue (876.2 MeV.cm^2/gm) is larger than that of the skeletal tissue (763.1 MeV.cm^2/gm). The range of protons in the material increases by increasing the energy and its value also depends on the rate of energy loss; hence, its value in the skeleton is larger than that in the intestine tissue, as shown in Figure-7. Depending on the range values calculated by the SIRM program, the maximum absorbed dose of the skeleton tissue was 4.8*10 $^{-6}$ rad at the range of 4.991 g/cm^2. For the intestine tissue, the maximum absorbed dose was 4.8*10 $^{-6}$ rad at the range of 4.651 g/cm^2, because the energy loss in the intestine was larger than that in the skeleton tissue.

Table 2-Maximum mass stopping power, maximum range , and maximum absorbed doses calculated along the path of the proton in human skeleton and intestine tissues, with maximum percentage error (%) of stopping power calculated by four methods.

Tissue	**Method**	**Energy (Mev)**	**Maximum range of particle through the tissue (g/cm^2)**	**Maximum mass stopping power lost along particle path in target (MeV.cm^2/gm)**	**Maximum percentage deviation of stopping power (%)**
skeleton	Srim	0.08	0.3014	793.1608	1.0193
	Beth	0.15	0.4550	517.1009	12.5296
	Ziegler	0.06	0.1564	830.4496	1.8585
	Casp	0.11	0.3018	684.7549	1.6508
	P.W	0.08	0.3407	763.1383	-
intestines	Srim	0.07	0.2822	902.6974	1.8835
	Beth	0.13	0.4305	609.3822	13.6106
	Ziegler	0.06	0.1459	977.6125	1.6001
	Casp	0.11	0.2820	771.9524	1.1039
	P.W	0.08	6.4026	876.1539	-

Conclusions

In this work, the range and the stopping power for protons in both the skeleton and the intestine tissues of humans were calculated because such studies have important applications in medical, biological and applied sciences. It was found that the SRIM program method was more efficient for the calculations than the other methods. The Beth method had a high rate of deviation because it depends on the values (***I***) .

References

1. H. Paganetti and T. Bortfeld. **2005**. "Proton Beam Radiotherapy" Massachusetts General Hospital, Boston, MA, USA New Technologies in Radiation Oncology (Medical Radiology Series) (Eds.) W. Schlegel, T. Bortfeld and A.-L. Grosu Springer Verlag, Heidelberg, ISBN 3-540-00321-5, October .
2. S. P. md, X. K. msc, M. Parliament md, and I. A. Olivotto md . **2014**. "Recommendations for the referral of patients for proton-beam therapy, an Alberta Health Services report: a model for Canada?" *Current Oncology*, **21**(5).
3. S. R. Manohara, S. M. Hanagodimath, L. Gerward. **2011**. "Energy absorption buildup factors of human organs and tissues at energies and penetration depths relevant for radiotherapy and diagnostics". *Journal of Applied Clinical Medical Physics*, **12**(4): 296-312.
4. H. Paul, O. Geithner, O. Jäkel. **2007**. "The Influence of Stopping Powers upon Dosimetry for Radiation Therapy with Energetic ions ,"*advances in quantum chemistry*, **52**, ISSN: 0065-3276 DOI: 10.1016/S0065-3276(06)52013-1. 2007
5. A. N. Habte. **2011**. "Calculations of stopping power and range of alpha particles of several energies in different materials" thesis at Addis ababa university addis ababa, Ethiopia june .
6. H.H Andersen, J.F. Ziegler. **1977**. " Hydrogen stopping power and ranges in all elements", vol.3, Pergamon Press Inc., Maxwell House, Faiview Park, *Elmsford, U.S.A.* 1977.
7. J. E. Ziegler. **1985**. "The Stopping and Range of Ions in Solids", Pergamon Press, New York.
8. P. g. Rancoita, L. Claude. **2015**. *"Principles Of Radiation Interaction In Matter And Detection"*. World Scientific.
9. A. Poškus. **2020**. " Absorption of alpha particles and electrons" Vilnius University Faculty of Physics Department of Solid State Electronics Laboratory of Atomic and Nuclear Physics , 2020.
10. S.Y. Lee. **2010**. "*Accelerator Design for Proton Therapy* ", Indiana University.
11. B. David. **2007**. "Nuclear energy: principles, practices, and prospects" Springer Science & Business Media.2007