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Calculation of the Absorbed Dose From Single Electron Beam Using Stopping Power Data

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Abstrak. The radiation energy of electrons will decrease when interacting with a medium due to stopping power. In this study, calculations were performed to determine the reduction of electron beam energy and absorbed dose, assuming the electron motion does not change direction, so radiation stopping power can be neglected. Electron beams with initial energies of 6, 8, and 10 MeV were observed interacting with air, water, and adipose tissue. Graph plotting and integral processing were conducted using OriginPro 8.5 software. Absorbed dose calculations were performed at 100 cm in air, 1 cm and 2 cm in water and adipose tissue, using electron Collision Stopping Power data. The research results indicate that the electron path range in the medium will increase with increasing electron energy and decreasing medium density, with the farthest range observed when electrons are in air. Absorbed dose is directly proportional to Collision Stopping Power; it is known that absorbed dose will increase with increasing electron energy and decrease with electron path length. This study confirms the decrease in electron energy and absorbed dose with energies of 6, 8, and 10 MeV.

Keywords: Stopping Power, Absorbed Dose, Electron Beam

I. Introduction

Radiotherapy uses beams of radiation, either photons or particles, to kill cancer cells. The radiation beam energizes the medium through which it passes in the form of a radiation dose, which is expected to kill the target cancer cells. The absorbed dose is defined as the amount of radiation energy transferred to the medium per unit mass of the medium through which the radiation beam passes. The unit for radiation dose is J/kg or Gray (Gy).

The radiation of charged particles when interacting with the medium will experience a reduction in energy due to interacting with the particles in the medium. The amount of energy reduction is affected by the Stopping Power of the medium. Stopping power is defined as the amount of energy reduction from a charged particle beam per unit length of the path traversed in a medium ($S = dE/dx$). Stopping Power is classified into two types, namely Collision Stopping Power and Radiative Stopping Power. Collision Stopping Power, the reduction in the energy of charged particles is caused by a collision between the particle beam and the particles in the medium, the processes that cause Collision stopping power are excitation and ionization events. Radiative Stopping power, a reduction in electron energy due to the Bremsstrahlung event which results in photons being emitted [1].

Energized electron beams can be generated from particle accelerators, for example for muon particle simulations it can be done by accelerating electrons to a certain energy [2]. A linac is a device used to accelerate electrons to a certain energy, where this electron beam can be used directly for radiotherapy or applied to X-Ray targets, so the beam used for therapy is a photon beam [3]. The use of electron beams for radiotherapy is added with the installation of an applicator to guide the direction of the electron beam, minimizing the deflection of the direction of electron motion.

II. Method

The electron beam dose was determined using the Stopping Power data in this study. The data source for Stopping Power, CSDA and Density Effects used came from https://physics.nist.gov which was then expressed graphically using OriginPro 8.5 software, so that a graph of the relationship between Stopping was obtained. Power, CSDA and Density Effects as a function of electron energy. The assumption used is that as long as the movement of electrons in the medium has a trajectory in the form of a straight line, ignoring the effects of scattering or deflection of the direction of electron motion due to interaction with the medium, this assumption was chosen because in clinical conditions during radiotherapy treatment using Linac, an applicator was installed which functions to keep electrons moving in a straight line. Thus the next calculation only uses Collision Stopping Power.

The electron energy will decrease continuously as a function of its trajectory distance, to determine the relationship between the reduction in electron energy and its trajectory distance, it is carried out by performing an integral $x = \int \frac{dE}{S}$ then inversion of the equation to obtain a graph of the relationship between the reduction of electron energy and its trajectory distance. , this process is done using Origin Pro 8.5 software. Determination of the absorbed dose is carried out using equation D=ϕ S_col/ρ for the electron fluency value of 1 cm-2. The amount of Collision Stopping Power is determined by linear interpolation on the energy of electrons when they have penetrated air as far as 100 cm, water and adipose tissue after penetrating 1 cm and 2 cm.

III. Result and Discussion

Desain Produk Comparison Stopping Power of Air, Water and Adipose Tissue

The loss of energy of charged particles is known because there are two events, namely due to collisions (Ionization), resulting from interactions with electrons in atomic shells, or what is often called Collision Stopping Power (Scol) [4]. Energy loss is also caused by Radiative Stopping Power (Srad), which results from the interaction of charged particles with atomic nuclei [5]. The Electron Collision Stopping Power equation based on the ICRU is as follows:

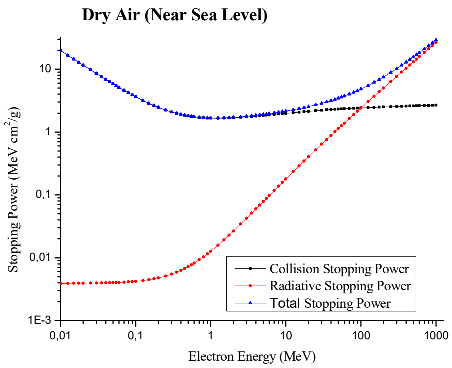
$$\frac{S_{col}}{\rho} = \frac{N_A Z}{A} \frac{\pi r_e^2 2 m_e c^2}{\beta^2} \left[\ln\left(\frac{E_k}{I}\right)^2 + \ln\left(1 + \frac{\tau}{2}\right) + F^-(\tau) - \delta \right] \quad (1)$$

Where NA Advogadro Constant, A Mass Number of medium, Z atomic number of medium, re classical radius of electron, Ek kinetic energy of electron, I average excitation potential of medium, v velocity of elektron, c velocity of light, me rest mass of elektron, δ Density effect correction, $\tau = E_k/m_e c^2$, $\beta = v/c$, and $F^-(\tau) = (1-\beta)\left[1 + \frac{\tau^2}{8} - (2\tau + 1)\ln 2\right]$.

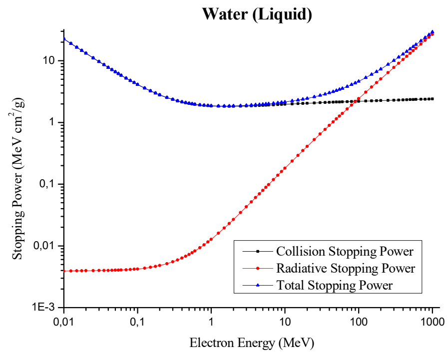
Radiative stopping power is the loss of electron energy due to Bremsstrahlung. According to the Bethe-Heitler theory, the radiative stopping power equation for electrons is as follows:

$$\frac{S_{rad}}{\rho} = \sigma_0 \frac{N_A Z^2}{A} (E_k + m_e c^2) \overline{B_r} \quad (2)$$

Where $\sigma_0 = \alpha(e^2/4\pi\varepsilon_0 m_e c^2)^2$, α is a fine structure and $\overline{B_r}$ is a function of Z and Ek, whose values are between 5.33 – 15 for the energy range 0.5 – 100 MeV. Based on equations (1) and (2), it can be noted that the Stopping Power is a function of the radiant energy of charged particles [6]. Figure 1 shows the Stopping Power of electrons when they are in air, water and adipose tissue, it can be seen that for low energy the dominant Stopping Power is collision stopping power, while for high energy the dominant is radiative stopping power.



(a)



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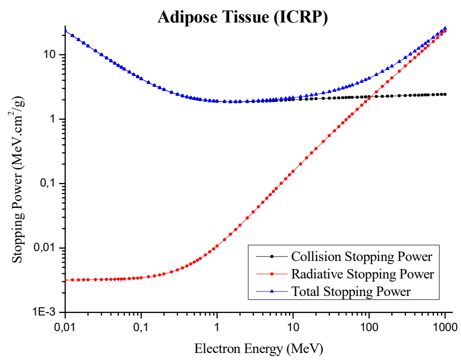


(c)

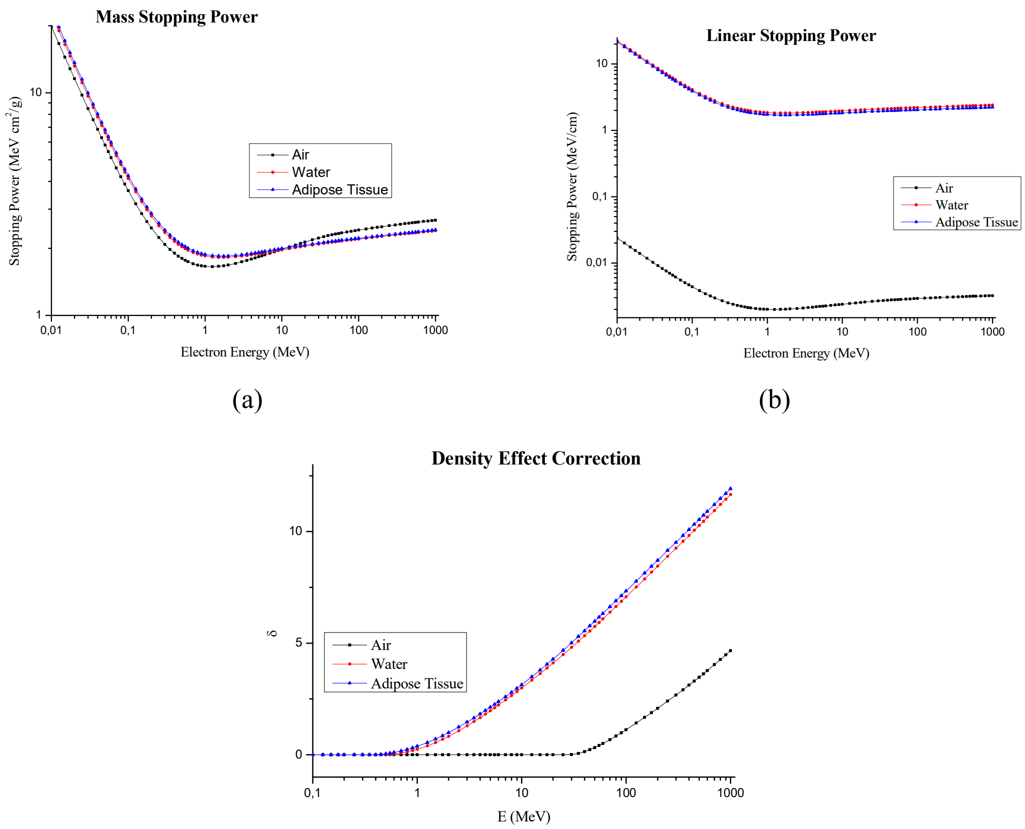
Figure 1 Stopping power electrons in (a) dry air near sea level and (b) water in the liquid phase (c) Adipose Tissue (ICRP) [7].

Electrons are light particles, so during their interaction with the medium it is easier to experience a scattering process, which causes the direction of motion to change from the original direction of motion. This change in the direction of electron motion has the potential to cause energy loss due to the Bremsstrahlung process or radiative stopping power. In the use of a Linac for radiotherapy with an electron beam, an applicator is attached which functions to keep the movement of electrons in a straight line so that an electron beam with the desired irradiation area is obtained. Because the electron trajectory can be kept in a straight line, the effect of radiative stopping power caused by the Bremsstrahlung can be minimized. So that the electron beam studied in this study is an electron beam with energy such as the output from the Linac, and during its journey electron interacts with the particles of the medium being traversed, Air, Water and Adipose Tissue. Figure 2 shows a comparison of the Collision Stopping Power of electrons in Air, Water and Adipose Tissue.

In Figure 2 (a), it can be seen that the Mass Stopping Power for air, water and Adipose tissue has almost the same value for all energy spectra, this is as previously explained that this Mass Stopping Power reduces the dependence of stopping power on the density of the medium, However, correction of the density effect (δ), as written in equation (1) can be observed, namely for the Air medium begins to be observed at an electron with an energy of 30 MeV, for Water at an electron with an energy of 0.55 MeV and in the Adipose tissue at an electron with an energy of 0 ,45 MeV. In Figure 2 (b) which depicts the Linear Stopping Power of Air, Water and Adipose tissue, it can be seen that the Air has a much smaller Stopping Power than Air and Adipose tissue, because the density of air is much smaller than that of Water and Adipose Tissue.

Based on the energy range selected in this study, there is no correction of the density effect in the air medium. The electron beam has an energy of 6 MeV, for water it has $\delta = 2.227$ and for Adipose Tissue it has $\delta = 2.379$. The electron beam has an energy of 8 MeV, for the water it has $\delta = 2.652$ and for the Adipose Tissue it has $\delta = 2.798$. The electron beam has an energy of 10 MeV, for the water it has = 2,992 and for the Adipose Tissue it has = 3.138. It is observed that the density correction is proportional with the energy of the electron beam, as in Figure 2 (c), based on equation (1) the magnitude of will cause a reduction in the value of the total

Stopping Power, this indicates that the increasing the energy of the electron beam, the Collision Stopping Power will become smaller, as shown in figure 1 and figure 2



(c)

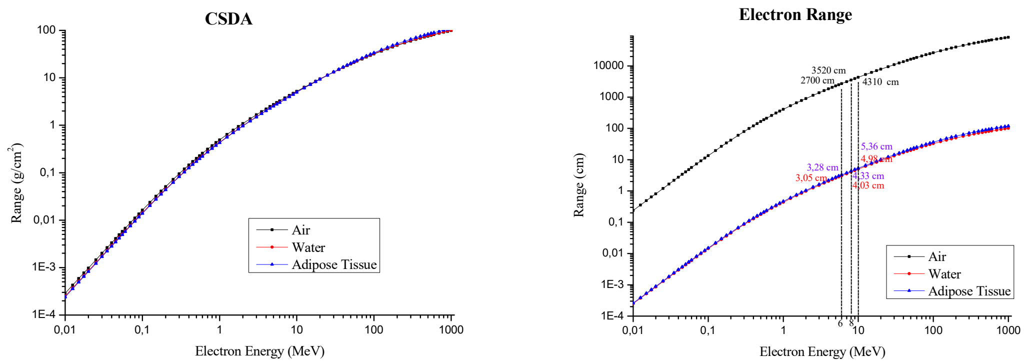
Figure 2. Comparison of Collision Stopping Power from Air, Water and Adipose Networks (a) Mass Stopping Power (b) Linear Stopping Power (c) Density effect correction [7].

Continuous Slowing Down Approximation of Air, Water and Adipose Tissue

An electron along its path in a medium will experience a quasi-continuous loss of energy so that it will eventually stop. This means that electrons will have a limited range in a medium [8], in contrast to photons when interacting with matter their intensity decreases exponentially [9]. The range of electrons, or charged particles in general, interacting with this medium is called the Continuous Slowing Down Approximation (CSDA), which is formulated as follows:

$$R_{CSDA} = \int_{E_0}^{0} \left[\frac{S(E)}{\rho}\right]^{-1} dE \tag{3}$$

Where RCSDA is the range of CSDA defined as the total length of the path of the charged particle, the electron. This RCSDA is different from the penetration distance, because the penetration distance is measured based on the initial direction of the electron through a medium [3]. Figure 3 shows the RCSDA curve of electrons interacting with the medium of Air, Water and Adipose tissue.



(a) (b)

Figure 3. Range of electrons when passing through the air, water and adipose tissue (a) using Mass Stopping Power, in g/cm2 (source https://physics.nist.gov) and (b) Using Linear Stopping Power, in cm.

The range of RCSDA, using equation (3) is depicted in Figure 2 (a) with units of g/cm2, it can be seen that the RCSDA for Air, Water and Adipose tissue have values that are not much different, this is because in the calculation using the mass stopping power that reduce its dependence on the density of the medium. This RCSDA calculation involves all the constituents of the Stopping Power of a medium, namely both radiative and Collision. RCSDA is expressed in cm, as shown in Figure 2 (b), by entering the density of each medium, in general, RCSDA for water and adipose tissue will have values that are close to each other, while in air the range of electrons will be far away. once, this is because the density of air is small so that electrons are able to travel in air over relatively long distances.

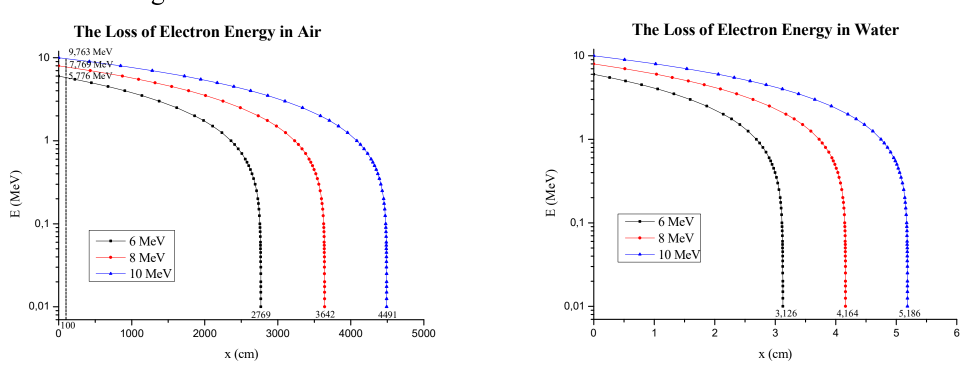
Figure 2 (b) provides information that an electron with an energy of 6 MeV has an RCSDA of 2700 cm in air; 3.05 cm in Water and 3.28 cm in Adipose tissue. An electron with an energy of 8 MeV has an RCSDA of 3520 cm in Air; 4.03 cm in Water and 4.33 cm in Adipose tissue. An electron with an energy of 10 MeV has an RCSDA of 4310 cm in Air; 4.98 cm in Water and 5.36 cm in Adipose tissue. The magnitude of the RSCDA is theoretically the longest path that electrons can travel when interacting with a medium. From the data it can be seen that the greater the energy of the electron beam, the longer the path that can be passed.

Electron Energy Decrease as a function of Path

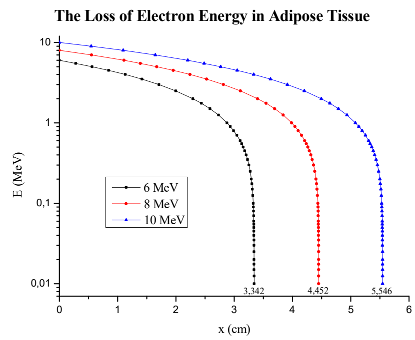
The data shown in Figure 3 (b) is Linear Stopping Power data as a function of Energy, S(E) = dE/dx. To obtain the energy reduction as a function of the distance between the electrons, the following equation is used:

$$dx = \int \frac{dE}{S(E)} \tag{4}$$

In equation (4) the equation x will be obtained as a function of E, so that by performing the inversion of equation (4) it will be obtained the relationship of the reduction in electron energy as a function of the distance of the path as shown in Figure 4.



(a) (b)



(c)

Figure 4. Energy as a function of trajectory of the electron beam passing through (a) Air, (b) Water and (c) Adipose tissue.

When the electron beam interacts with air, its energy will continuously decrease as a function of the distance traveled, as shown in Figure 4(a). From the figure, it can be seen that electrons with an energy of 6 MeV are able to pass through the air with a path length of 2769 cm, electrons with an energy of 8 MeV are able to pass through the air with a path length of 3642 cm, while electrons with an energy of 10 MeV are able to pass through the air with a path length of 4491 cm. before the electrons finally stop. The magnitude of the results of this calculation is close to the RCSDA of electrons in the air, namely for an energy of 6 MeV having an RCSDA of 2700 cm, 8 MeV having an RCSDA of 3520 cm and 10 MeV having an RCSDA of 4310 cm.

When the electron beam interacts with water, its energy will continuously decrease as a function of the distance traveled, as shown in Figure 4(b). From the figure, it can be seen that electrons with an energy of 6 MeV are able to pass through water with a path length of 3.126 cm, electrons with an energy of 8 MeV are able to pass through water with a path length of 4.164 cm, while electrons with an energy of 10 MeV are able to pass through water with a path length of 5.186 cm. before the electrons finally stop. The magnitude of the results of this calculation is close to the RCSDA of electrons in water, namely for an energy 6 MeV having an RCSDA of 3.05 cm, 8 MeV having RCSDA of 4.03 cm and 10 MeV having RCSDA of 4.98 cm.

Figure 4(c) shows electron beam reduction when interacting with adipose tissue as a function of the path distance. From the figure, it can be seen that electrons with an energy of 6 MeV are able to pass through the Adipose network with a path length of 3.342 cm, electrons with an energy of 8 MeV are able to pass through the Adipose network with a path length of 4.452 cm while electrons with an energy of 10 MeV are able to pass through the Adipose network with a path length of 5.546 cm, before the electron finally stopped. The result of this calculation is close to the electron RCSDA in the Adipose network, namely for an energy of 6 MeV having an RCSDA of 3.28 cm, 8 MeV having RCSDA of 4.33 cm and 10 MeV having RCSDA of 5.36 cm.

The maximum path range obtained from the calculation results in a value greater than the RCSDA, this is because in this study the calculation is carried out only with Collision Stopping Power, thus ignoring the effect of radiative stopping power. However, the range results obtained are close to the electron RCSDA for each medium. The results obtained confirm that, at the low energies selected in the study, for calculating the absorbed dose using stopping power, the effect of radiative stopping power is negligible. However, when the electron energy is high enough, the effect of radiative stopping power can no longer be ignored, because as shown in Figure (1), the radiative stopping power will be more dominant when the electron has a high energy.

Calculation of Electron Absorbed Dose

The electron beam when interacting with the medium will lose its energy during its journey, this energy is transferred to the medium, in this case through a collision process, so that the absorption dose calculation uses Collision Stopping Power as shown in equation bellow:

$$D = \phi \frac{S_{col}}{\rho} \quad (5)$$

In this study, the absorbed dose calculated is the absorbed dose contributed by an electron in the medium, or in other words, the electron fluency in equation (5) is chosen to have a value of 1 cm-2. So that the amount of absorbed dose referred to in this study is the same as the amount of Collision Stopping Power, it can be written as follows:

$$D = \frac{S_{col}}{\rho} \tag{6}$$

Based on Figure 4, electrons are able to penetrate the air with a fairly long trajectory distance, so that the calculation of the electron absorption dose is carried out at a trajectory distance of 100 cm, which is in accordance with SSD in radiotherapy treatment using Linac. Meanwhile, in water and adipose tissue, the absorbed dose was calculated at a distance of 1 cm and 2 cm, which represents the dose depth. The results of this dose calculation as shown in table 1, it can be seen that the greater the energy of the electron beam, the higher the dose received by the medium.

Table 1. Calculation of Electron Absorbed Dose

Material	Depth	Electron Initial Energy (MeV)	Electron Energy in Depht (MeV)	$D = \frac{S_{col}}{\rho}$ (MeV.cm2/g)
Air	100 cm	6	5,776	1,855
		8	7,769	1,924
		10	9,763	1,973
Water	1 cm	6	4,108	1,873
		8	6,072	1,912
		10	8,044	1,944
	2 cm	6	2,257	1,829
		8	4,178	1,874
		10	6,116	1,913
Adipose Tissue	1 cm	6	4,230	1,903
		8	6,198	1,942
		10	8,172	1,974
	2 cm	6	2,498	1,860
		8	4,424	1,907
		10	6,367	1,945

The electron beam interacting with air is capable of traveling on a fairly long path, the reduction in its energy when traveling in air for an electron beam of 6 MeV at a trajectory distance of 100 cm the energy is reduced to 5.776 MeV, this electron energy difference is absorbed by the medium and becomes an absorption dose along the 100 cm path. cm, as for the absorption dose at a point that is 100 cm away from the electron beam source of 1.855 MeV cm2/g, as for the complete data for different electron beam energies can be seen in table 1, this value is the absorption dose contributed by an electron particle in air at a distance of 100 cm from the electron beam output source. In practical conditions of radiotherapy treatment, the dose obtained at a distance of 100 cm is the absorbed dose received by the patient's body surface, or what is often referred to as the surface dose. By using this value, it can be used to calculate the amount of electron fluency generated by the electron beam radiation source, in this case the Linac.

The electron beam that interacts with Water or Adipose tissue has a maximum path that is almost the same, but is much shorter than the maximum path in Air. At a depth of 1 cm and 2 cm in these two mediums, the energy of the electron experienced a significant reduction in energy, and the absorption dose data at that depth can be seen in full in table 1. The amount of dose listed in table 1 can be used as a prediction of the dose depth in a given medium or organ, as shown in figure 5.

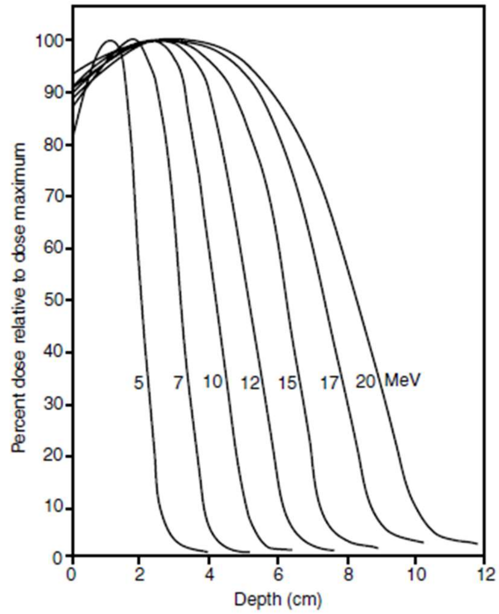


Figure 5. The percentage dose depth at the center of the electron beam has an energy of 5 MeV to 20 MeV [9].

The electron beam that penetrates the organ will provide an absorption dose as depicted in Figure 5, this absorption dose is a function of depth, in the figure it can be seen that the electron beam is only able to penetrate the organ at a certain distance before finally stopping. But at the end of the movement of electrons there is still an observed absorption dose, this dose is contributed by the photons that are formed during the electron interacting with the organ, the remaining dose is called the Bremsstrahlung tail [6]. In this study, the Bremsstrahlung tail was not observed, as shown in Figure 4, because it used the approach that the Stopping Power used was only Collision, while the contribution of the radiative was ignored. the medium will have a finite range, unlike photons whose range is not limited because the reduction in intensity is confirmed exponentially [10].

IV. Conclusion

Based on the results of the studies that have been carried out, it can be concluded that the electron beam when interacting with the medium, has a limited range of trajectories before finally losing all of its energy. The range of the electron beam trajectory is influenced by the energy of the electron beam and the density of the medium through which the electron beam travels. The absorption dose given to the medium will decrease along with the depth of the electrons penetrating the medium, the greater the energy of the electrons, the higher the absorption dose will be.

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