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Characteristics Analysis of High Energy External Radiotherapy Beams in Water

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ABSTRACT

High energy external radiotherapy beam is being used widely for cancer treatment. Biological effect of radiation is concerned with the evaluation of energy absorbed in the tissue. The study of photon and electron beam characteristics is necessary before calibration machine. The aim of this study was to analysis characteristics of depth dose of different energy beams in water to enhance the quality of the radiotherapy treatment planning. Beam is attenuated by the medium and the transmitted beam with less intensity causes lesser absorbed dose as the depth increases. Relative attenuation on certain points on the beam axis and certain percentage of doses on different depths for 4-15 MV photon beams and 4-18 MeV electron beams have been investigated. Depth dose characteristics of the beams do not show identical attributes as interaction of the beams with matters is mainly governed by beam quality. Attenuation and penetration parameters show variation with dosimetric parameters like field size due to scattering and source to surface distance due to inverse square law but the major parameter in interaction is energy. Detailed analysis of the beam characteristics helps to select appropriate beam for radiotherapy treatment when variety of beam energies available and hence to increase accuracy in radiotherapy treatment.

Key words: Radiation, Photon Beam, Electron Beam, Absorbed dose, Percentage Depth Dose and Treatment Planning

Highlight: Depth dose characteristics of external beam helps to select appropriate beam for radiotherapy treatment.

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INTRODUCTION

Radiation therapy refers to the treatment of malignant disease by using high energy radiation to kill the malignant cells or change genes so that cells stop growing. The energy beams affect the cells along their path as they go through the body to get to the cancer, pass through the cancer, and then exit the body. The goal is to deliver enough radiation doses to the tumor to destroy it while still limiting the dose to surrounding tissues (P. Metcalf et al., 2004). High-energy photon and electron beams are the most common form of radiations that have been used for cancer treatment. Linear accelerator is the most commonly used device that can generate an electron beam at various energies together with photon beam.

Selection of appropriate set of treatment planning parameters is vital for determination of dosimetric characteristics of all radiation beams. Data on the percentage depth-dose of diagnostic X-rays are important in evaluating patient dose from medical exposure (Besim Xhafa *et al*, 2014 and Kato H *et al*, 2004). Quality of a radiation beam is most usefully expressed in terms of its penetrating power in radiotherapy which is a function mainly of the mean photon energy, and may be fully described by its depth dose characteristics in water (G.Narayanasamy *et al*, 2015) but an increase in surface dose with field size is also noted due to electron scattering from intervening materials (Khan F.M, 2003).

The fundamental physical quantity of interest for relating radiation treatment to its outcome is the absorbed dose. Basic data of dose distributions usually derive from measurements in phantoms, and then use in a dose calculation system devised to predict dose distribution in an actual patient (Ravikumar M *et al*, 2002.). These phantoms are tissue equivalent and are made of different materials and different methods (White DR, *et al*, 1977). Dosimetry is a very significant element of radiotherapy treatment as all the treatment planning is based on the data obtained during dosimetry. Optimization of treatment plan, and calculation of dose for certain plan is performed when radiation physicist have measured dosimetry data.

Absorbed dose in the body is dependent on depth, field size, beam energy and source to surface distance (SSD). Measurement of absorbed dose is performed using water or any other equivalent media phantom, which is kept perpendicular to the path of beam. This measurement is expressed as Percent of dose which gives a unique value for a certain set of parameters like beam energy, depth, SSD and field size. Variation in this value can be noted by change in any of these parameters (Wambersie A, *et al*, 2002). Beam which traverses a medium, the fluency decreases with increasing the depth but its energy stay practically constant and the percentage depth dose curve in ionization merges with the PDD curve in dose.

MATERIAL AND METHOD

It was intended to explore characteristics of high energy photon and electron beams of diverse range because of widely used for treatment of cancer patient. Doses were measured in water as it is always assumed to be a better phantom for being very close to human body due to its density and number of electrons per gram and universally available with reproducible radiation properties. The special supplement of British Journal of Radiology (BJR 25) serves as a guiding protocol for radiotherapy practices. The data of 10 cm × 10cm field size for different energies were analyzed and examined the depths of maximum dose and depths where dose fall to half of its maximum value, d_{50} . The relationship between these depths according to beam energy have been investigated specially the difference between these two depths was examined in view point of beam energy. The distance function between these two dose levels was then compared for different beam energies to analyze the average decrease in dose with depth.

Depth dose curve consists of two regions, the initial build-up region to the dose maximum followed by the exponential decay region which represents simple exponential attenuation in the water phantom. The important points such as dose at a depth of 0 cm and dose at a depth of 10 cm were located on the depth dose. These values are different for different field sizes even for same energy and source-to-surface distance (SSD). Similarly different depths can also be explored which gives a certain percentage of doses like depth of the maximum value of absorbed dose; d_{max} and depth of 50 % dose; d_{50} .

The surface dose can give an indication of the beam spectrum, for it is mostly due to the very low energy components of the beam. It is a general rule for photon that surface dose decreases with increasing beam energy and for any given beam energy increases with degradation of the spectrum towards the low energies. Unlike photon beams, the surface dose for electron increases with the increase in beam energy. High surface dose can have detrimental effects on the skin of therapy patients so it is desirable to minimize the surface dose. Relative attenuation can also be checked by comparing depths of certain percentage of dose rather than using doses at certain depths.

The surface doses of a certain energy and field size were examined. It increases with increase both in energy and field size independently. Attenuation, penetration and scattering of beam results in a unique value of absorbed dose are function of depth, field size, source to surface distance, beam energy and the absorbing material. MEPHISTO software was used to analysis the beam parameters.

RESULTS AND DISCUSSION

For Photon

Absorbed dose is a quantity which is used to quantify the exposure of biological objects to ionizing radiation. Dose distributions along the beam central axis gives information required for an accurate dose description inside the patient. The dose is described usually as Percentage Depth Dose (PDD) which depends on the depth, field size, energy and source to surface distance (SSD). The depths of measurement are typically at d_{max} and 10 cm for verification of compliance with machine specifications, in addition to other depths required by the particular treatment planning system used in the department (E. B. Podrosak, Radiation Oncology Physics, A Hand book for Teachers and Students, p-194). PDD values measured at 10 cm for three specified photon beams are presented in the Table-1 and it can be seen that it increases with the beam energy.

Table.1: Measured and tabulated values for PDD(10) for photon energies in the range 4-15 MV

Energy in MV	PDD(Measured)	PDD(Tabulated)[8]
4	63.19	63.0
6	68.08	67.5
15	76.18	77.0

When radiation beam enters in medium attenuation takes place and percentage depth dose varies with depth due to the attenuation. A typical depth dose curves for the photon is shown in Fig.1 which shows the relation between percentage depth dose and depth in the medium. One important thing is that the maximum dose, d_{\max} is not at the surface but at some depths. This is because of the range of the secondary electron (Khan FM. 2003). The electrons that are excited at the surface, on average, will travel a distance before they deposit dose. Beyond the depth of maximum dose, the PDD varies exponentially with the depth.

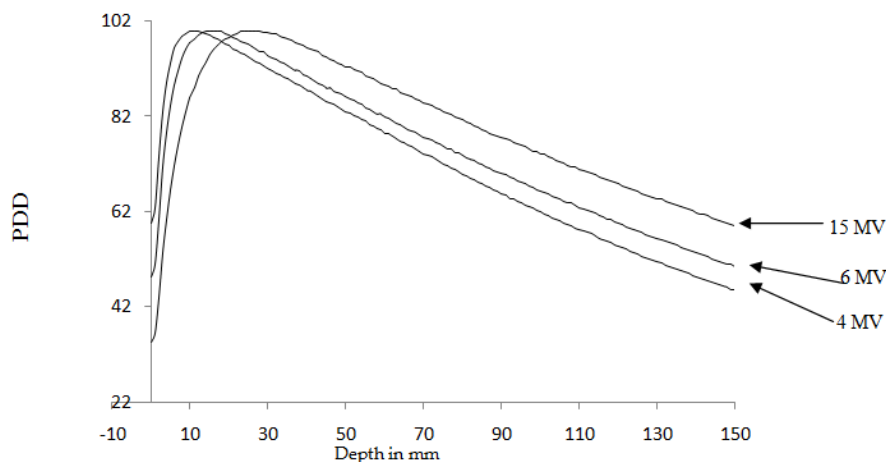


Fig.1: Cental axis depth dose distribution for different quality photon beams

The figure also indicates that for all energies the dose increases rapidly with the first few millimeters and then gradually achieves its maximum value at the depth of peak dose. In the case of 4 MV, the PDD increases from 59% to 83% in the first 3 mm, reaches 96% at 6 mm and achieves its maximum value at 11mm depth. Similarly maximum values occur at 15 mm and 25 mm for 6 MV and 25 MV photon beams respectively. Higher energy beams have greater penetrating power thus deliver a high percentage depth dose. With the increasing of the beam energy, the size of the chamber build up cap becomes excessively large and it is difficult to calculate the dose in free space from such measurement. The material of the build up cap different from the phantom introduces uncertainty in the tissue air ratio (TAR) measurements. To overcome the problem, the concept of tissue phantom ratio (TPR) was introduced for use in mega-voltage iso-centric setup (M. Jahingir Alam *et al*, 2007). It is a measure of effective attenuation coefficient describing the exponential decrease with the depth beyond the depth of maximum dose shown in the Fig. 2.

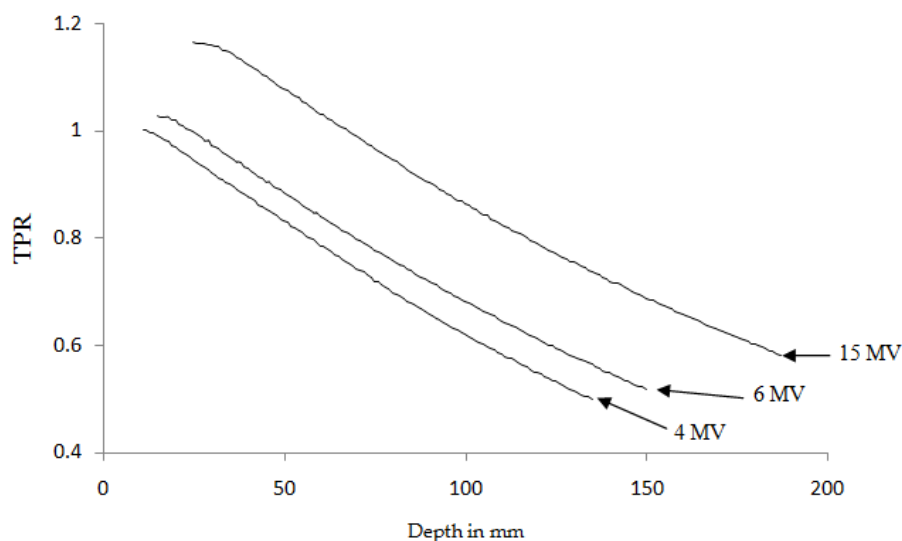


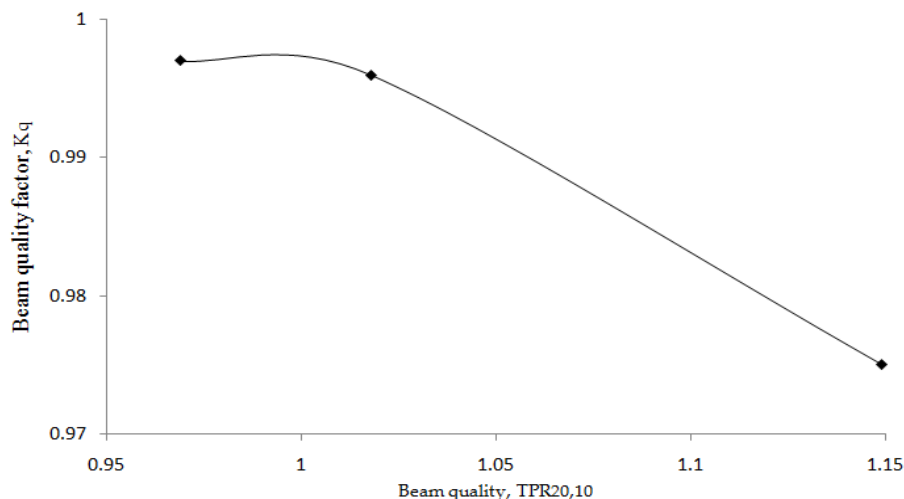
Fig. 2: Variation of Tissue phantom ratio (TPR) with Depth

Beam quality correction factor, K_q , is a beam quality specifying parameter. The uncertainty of various dosimetric factors tend to cancel out by the use of the factor. For high energy photons with beam quality, K_q is specified by the $TPR_{20,10}$ (M Saiful Huq *et al*, 2001). Both the parameters vary with the increasing beam energy. The data are presented in the Table-2.

Table 2: Measured values of $TPR_{20,10}$ and K_q for different photon beams

Beam Energy in MV	$TPR_{20,10}$	K_q
4	0.969	0.997
6	1.018	0.996
15	1.149	0.975

The variation can be seen better to view in the Fig.3 where beam quality factor, K_q decreases with the Tissue phantom ratio, $TPR_{20,10}$.

Fig.3: Beam quality correction factor, K_q as a function of beam quality parameter, $TPR_{20,10}$

The depths of maximum dose compared with depths of 50% dose for different beam energies. The difference between both depths increases with increase in beam energy. Table-3 shows that $d_{50}-d_{max}$ is increasing with beam energy but important is that there is a diverse mode of variation.

Table 3: Depth of maximum dose, depth of 50% dose and average decrease in percent dose per cm for photon beams of different energies

Energy in MV	Depth of 100% Dose in cm	Depth of 50% Dose in cm	$d_{50}-d_{max}$	Average decrease in percent dose per cm
4	1.1	13.57	12.57	4.0
6	1.5	15.22	13.72	3.64
15	2.5	18.98	16.48	3.04

The difference can be better to view in the Fig.4, where the relative difference between d_{max} and d_{50} of photon beams is plotted. The gap between curves seems to increase with energy to indicate a greater penetration. Less energy beam attenuates more than beam of higher energy. This relative attenuation analysis is helpful to analyse the beam attenuation, penetration and its ability to deliver the dose in specific increment of depth.

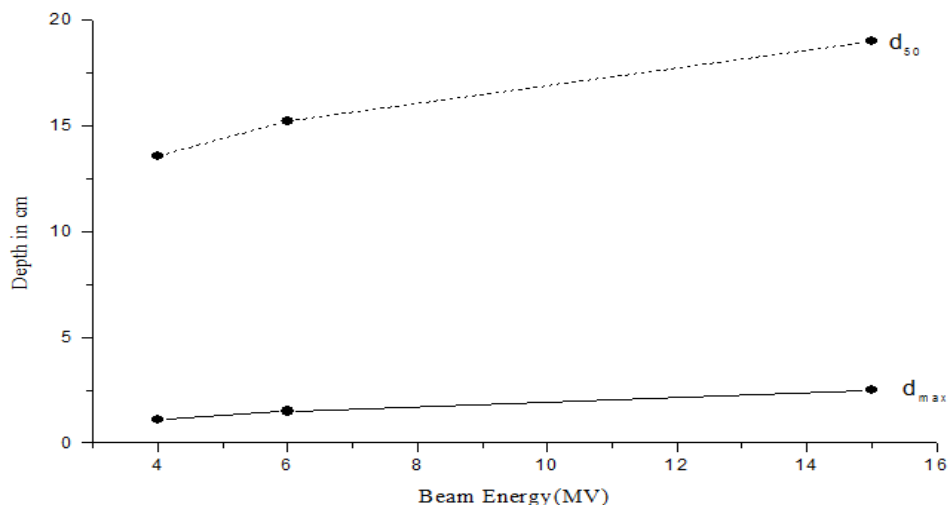


Fig.4: Depth of maximum dose and 50% dose with beam energy

The dose falls off in the region between d_{\max} and d_{50} can be evaluated with the average decrease in the dose per cm. The average decrease between these two depths decreases with increase in beam energy. The percentage depth doses for 4MV, 6MV and 15MV photon beams reduce to 4%, 3.64% and 3.04% per cm respectively. The relationship among these are obvious but the dose decrease rate do not have linear relationship. The reason is the mode of interaction with matter. The attenuation progression of high energy beam differs quite significantly from that of low energy beam because it interacts with matter with different attributes.

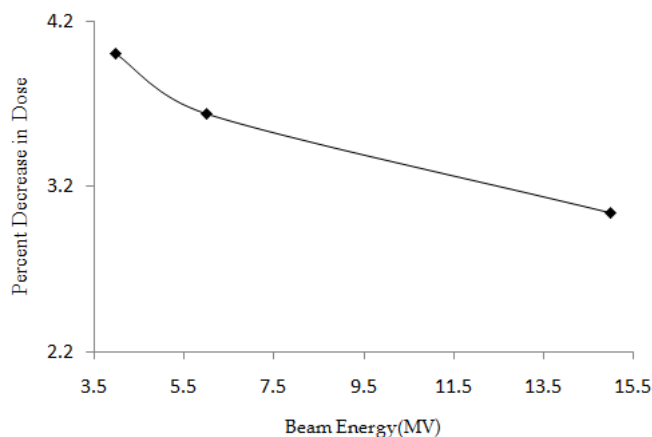


Fig.5: Average Decrease in photon dose beyond d_{\max}

Figure 5 shows the average decrease in dose in the region between d_{\max} and d_{50} . Here beam energy is plotted against PDD per cm and it can be seen that dose decrease is a function of energy. Average fall-off of the dose decreases with beam energy. This may not be a precise approach affirming the dose fall-off because it does not decrease in a continuous manner in the region between d_{\max} and d_{50} or decrease certain value after every cm. In comparing the dose build up with dose fall off, the dose at 0 cm (surface dose) is needed so that increase in dose per unit of thickness with the decrease in dose per unit thickness beyond the depth of maximum dose. Measured values of surface dose for three photon energies and different field sizes are presented in Table-4. The surface dose for 15 MV photon for 10cm x 10cm field size is 35.5% and the absorbed attain its maximum value on a depth of 2.5 cm. It exhibits an average increase of 26.5% dose per cm. Similarly, the other two-photon energy beams have relatively greater surface dose but a smaller value of d_{\max} . The surface dose will decrease while d_{\max} increases with increase in energy shown in Fig.6. This is not generalized numerically for all energy values due to the relative importance of various types of interactions between photon and matter.

Table 4: Surface dose of 4, 6 and 15 MV Photon beams for different field sizes

Field size (cm x cm)	4MV %	6MV %	15MV %
5x5	56.55	45.43	28.20
10x10	60.77	49.57	35.85
15x15	63.6	54.26	40.89
20x20	67.38	57.97	47.32
25x25	69.63	61.39	51.15
30x30	72.26	64.08	54.55

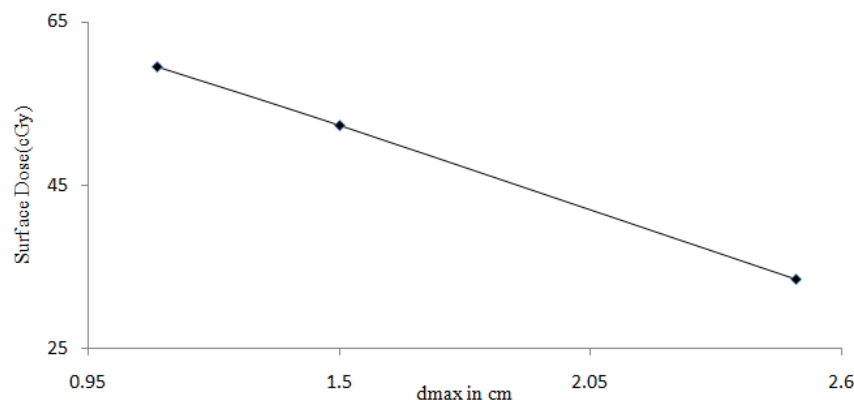


Fig. 6: Variation surface dose with d_{\max}

A photon beam propagating through a phantom is not only affected by the inverse square law but also by the attenuation or scattering of the photon beam inside the phantom. Beam energy influences isodose curve shape near field borders. Greater lateral scatter associated with lower-energy beams causes the isodose curves outside the field to bulge out. Therefore, the absorbed dose in the medium outside the primary beam is greater for low energy beam than that for higher energy beam. It can observe from the Fig. 7 that PDD(10) decreases with the absorbed dose in a very short region between d_{\max} and d_{90} for 4 and 6 MV photon beam. The rates of falling in PDD are 0.25 and 0.30 for 4 and 6 MV photon beams respectively where the rates of increasing in absorbed dose for the same energies are 0.05 and 0.037 respectively. This was absent in 15 MV photon beam shown in the Fig.7.

Therefore, it observes that the rate of falling increases in PDD but the rates of increasing in absorbed dose decreases with the increase of beam energy in the region of low energy. Sama Saed Al-Ahbabi *et.al.*, 2012 observed the same for 6 MV photon beam.

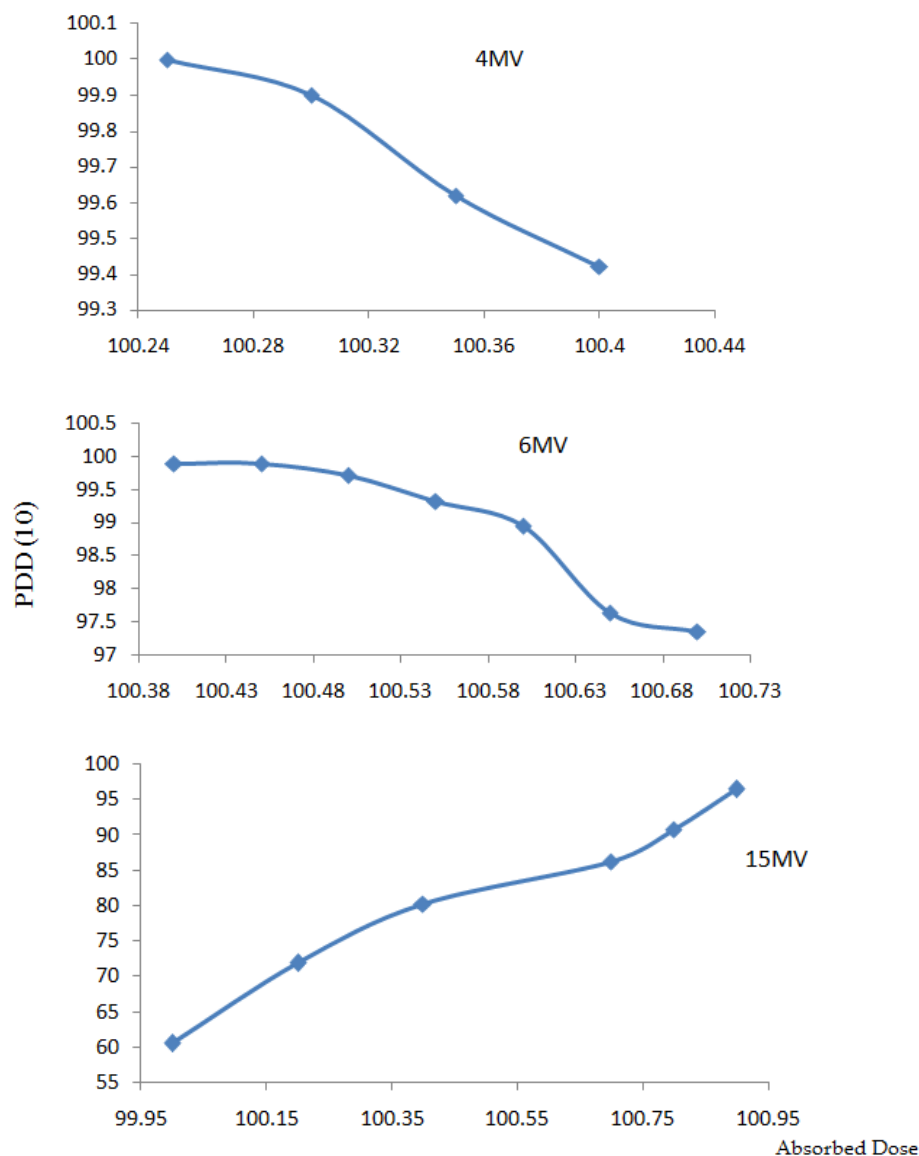


Fig7: Variation of PDD (10) with Absorbed Dose of different energies

For Electron

The measurement of percentage depth dose along the central beam axis given information required for an accurate dose description inside the patient was conducted for energies (4-18) MeV which varies with the beam energy. The general shape of the central axis depth dose curves for electron beams differs from that of photon beams are shown in the Fig.8 for a field size of 10 x10 cm².

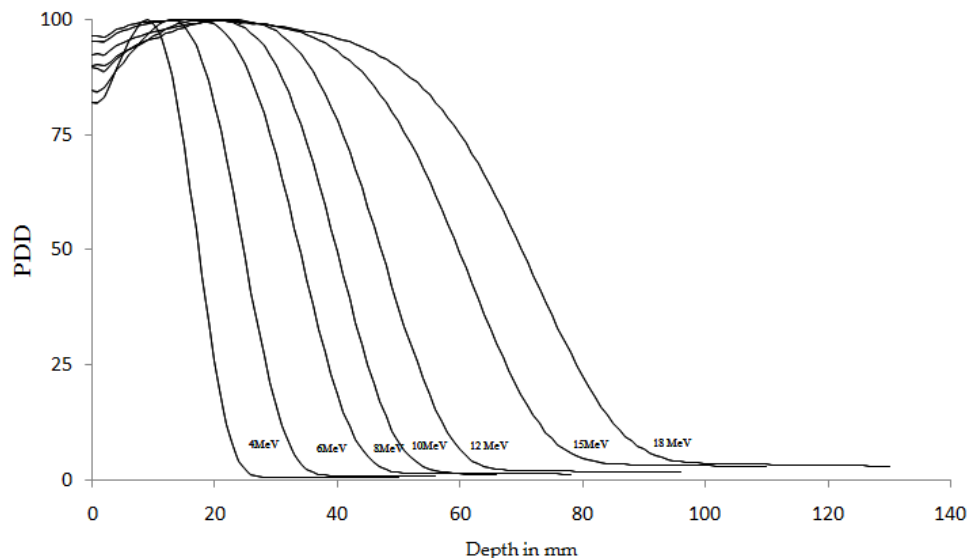


Fig.8: Cental axis depth dose distribution for electron beams

The important thing is that the maximum doses are at some depths but not at the surface. The depths are comparatively lower than those for photon beam energies. The change in depth dose curve for higher energies was because of large angular scattering of the electron beams (T. Arunkumar, et al., 2010). It can see in the figure that the surface dose of electron beams is much higher than that for photon beams.

Table 5: Surface dose and rate of increase of surface dose for different photon and electron beams

Beam Energy MeV	Surface dose for photon beam (%)	Surface dose for electron beam (%)	Rate of increase of photon surface dose [mm^{-1}]	Rate of increase of electron surface dose [mm^{-1}]
4	60.77	82.10	3.56	1.99
6	49.57	84.60	3.36	1.18
15	35.85	95.20	2.56	0.25

The percent surface dose for electron beams increases with the energy. This may occur due to the nature of electron scatter. The electrons are scattered more easily and through larger angles for lower energies. This causes the dose build-up more rapidly and over a shorter distance. The rate at which the dose increase from surface to maximum decreases with beam energy for both of the beams but it is less for electron beam than for photon beam shown in the Table 5.

The ratio of the surface dose (D_s) to maximum dose (D_{\max}) is lower for lower-energy electrons than for higher-energy electrons shown in the Table.6 Therefore, the factor (D_s/D_{\max}) increases with the increase in beam energy which can be better to view in the Fig. 9.

Table 6: Ratio of surface dose to maximum dose for different electron beam energies

Energy MeV	Ratio of surface dose to maximum dose
4	0.82
6	0.846
8	0.896
10	0.901
12	0.923
15	0.952
18	0.964

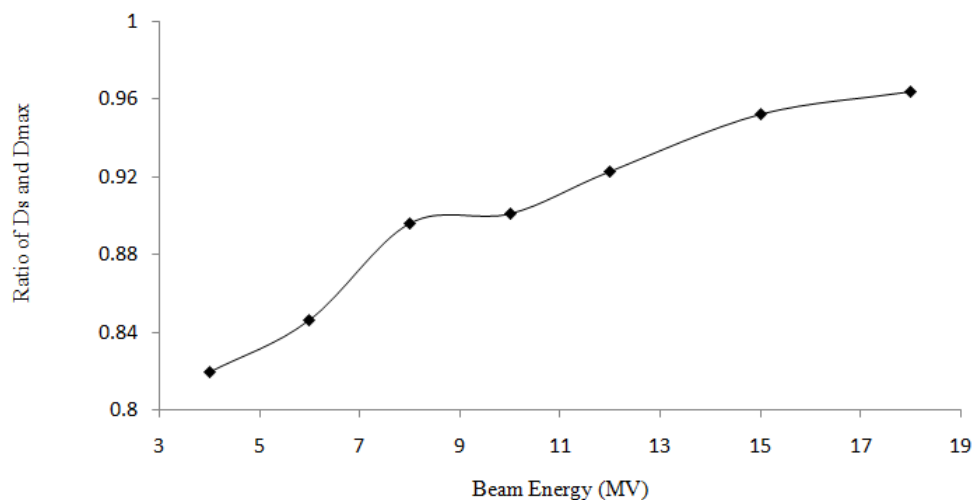
Fig. 9: Variation of D_s / D_{max} with the beam energy

Table 7: Typical Dose Parameters of Electron Beams

Energy MeV	R_{100}	R_{50} cm	R_{80} cm	R_{90} cm	\bar{E} MeV	$d_{50}-d_{max}$	Average decrease in percent dose per cm
4	0.9	1.732	1.413	1.216	3.94	0.832	60
6	1.299	2.488	2.033	1.822	5.80	1.189	42.05
8	1.70	3.421	2.795	2.508	7.97	1.721	29.05
10	2.100	4.046	3.327	2.997	9.43	1.946	25.69
12	2.299	4.797	3.935	3.538	11.18	2.496	20.03
15	1.802	6.092	4.879	4.30	14.19	4.290	11.65
18	1.400	7.158	5.732	4.971	16.68	5.759	8.68

The depth in centimeters at which electrons deliver a dose to the 80% to 90% is equal to about one-third to one-fourth of the electron energy in MeV shown in the Table.7. It can also see that the depth of maximum dose does not follow a linear relationship with the energy. The variation can be seen better to view in the Fig.10.

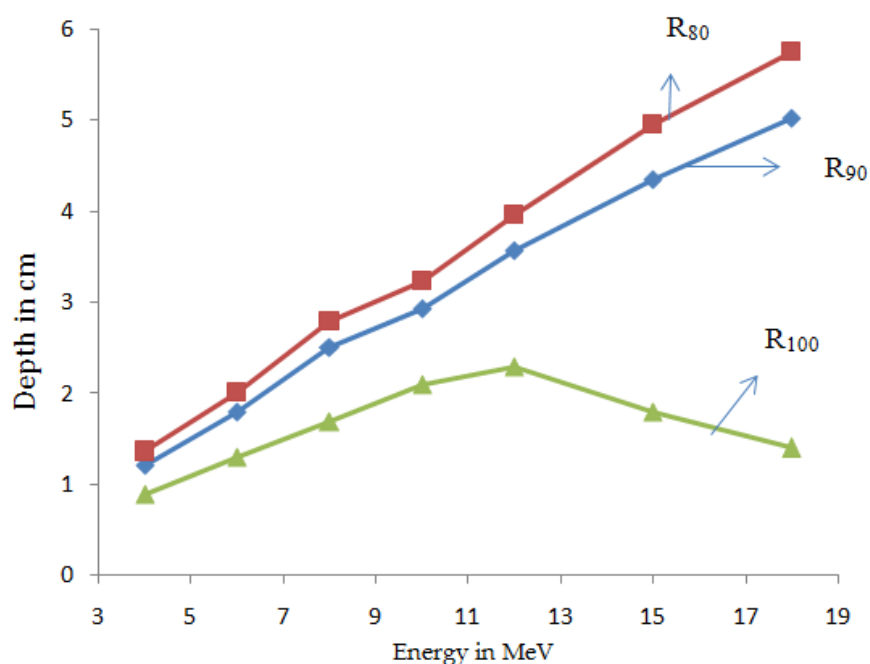


Fig.10: Variation of depths of maximum, 90% and 80% doses with beam energy

The dose falls off in the region between d_{\max} and d_{50} can be evaluated with the average decrease in the dose per cm. The data are given in Table 7. The average decrease between these two depths decreases with increase in beam energy. Percentage dose for 4 MeV electron reduces 60% per cm but the same is 8.68% for 18 MeV beam. The relationship between two energies is obvious but the dose decrease rates do not have linear relationship. The reason may be mode of interaction with matter. High energy beam interacts with different attributes with the matter and hence its attenuation progression differs quite significantly from that of low energy beams. The beam energy is plotted against percent dose decrease per cm in Fig.11 in the region between d_{\max} and d_{50} and it can be seen that average dose decrease is a function of energy and it falls off sharply. It can also be seen that the dose decrease does not follow a certain value after every centimetre. The similar trend also be noticed in the region between depth of maximum dose and depth of 90 and 80 % doses in Fig.11.

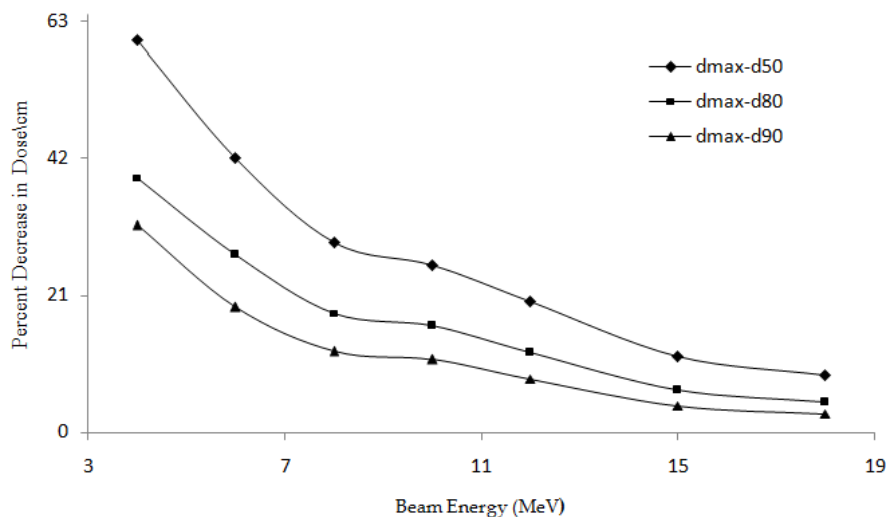


Fig.11: Average decrease in electron dose in the region beyond d_{\max}

The output dose varies with the field size. It can be seen from Fig.12 that output dose ratio for all electron beams reached its maximum at a certain field size ($10 \times 10 \text{ cm}^2$) with increasing field size and then decreases with further increasing in field size.

The intensity of the incident beam starts to decrease soon after its emission and it is significant after interacting with phantom material on its way. Intensity decreases continuously even in small fractions of depth changes. Therefore, incident electron has lower energy than that of the electron inside the accelerator given in Table 7.

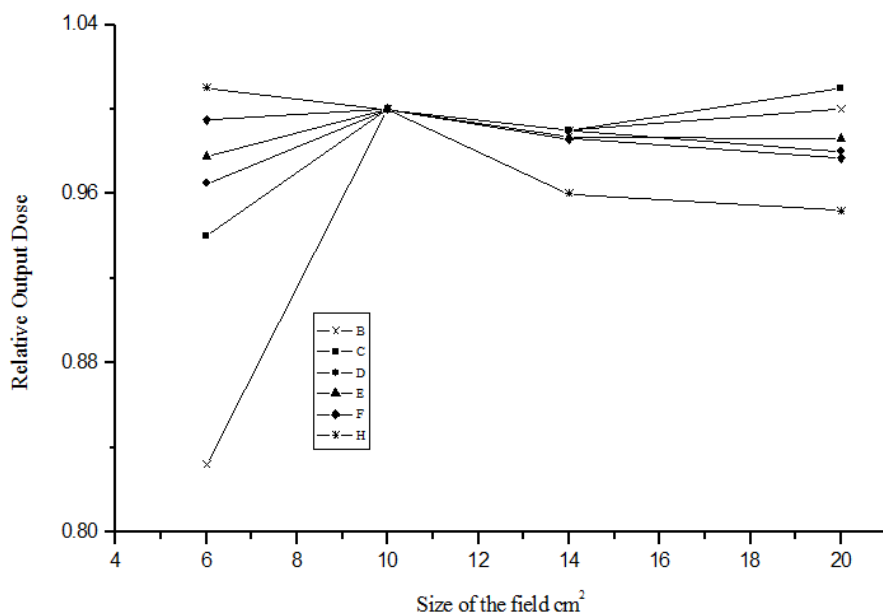


Fig. 12: Output dose for various field sizes of the electron beam

CONCLUSION

Characteristics analysis of depth dose for both the beams in radiotherapy treatment planning is helpful in achieving an increased degree of accuracy. Knowledge of energy and geometrical influence of different dosimetric parameters is indispensable for absorbed dose calculation. The clinically useful energy range for electron beams is 4 to 18 MeV. At these energies, the electron beam can be used for treating superficial tumor less than 5 cm deep with a characteristically sharp drop off in dose beyond the tumor. It may be noted that energy of photon beam is the major element of uniqueness of absorbed dose at certain depth in tissue or equivalent material. Due to other dosimetric consideration like field size and SSD, doses can have different values at certain location but the spectral and point to point distribution of the dose is the exclusive property of the beam energy. The detail analysis of the depth doses provides portions of depth containing a range and behavior of absorbed dose in water. Relative attenuation between two depths or between two doses describes the way in which dose decreases or increases for certain energy. The tumor or the target volume is never a small point. Keeping in view the shape and volume of the target along with its surrounding tissues require specific dose distribution. A beam capable of delivering the dose closely matching with the desired distribution always select for radiotherapy. The outcome of the present analysis will be helpful in view point to choose the appropriate beam for cancer treatment where a variety of beam energies is available.

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