AN ANALYSIS OF DEPTH DOSE CHARACTERISTICS OF PHOTON IN WATER

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Background: Photon beam is most widely being used for radiation therapy. Biological effect of radiation is concerned with the evaluation of energy absorbed in the tissues. It was aimed to analyse the depth dose characteristics of x-ray beams of diverse energies to enhance the quality of radiotherapy treatment planning. **Methods:** Depth dose characteristics of different energy photon beams in water have been analysed. Photon beam is attenuated by the medium and the transmitted beam with less intensity causes lesser absorbed dose as depth increases. Relative attenuation on certain points on the beam axis and certain percentage of doses on different depths for available energies has been investigated. **Results:** Photon beam depth dose characteristics do not show identical attributes as interaction of x-ray with matter is mainly governed by beam quality. Attenuation and penetration parameters of photon 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 photon interactions is its energy. **Conclusion:** Detailed analysis of photon Depth Dose characteristics helps to select appropriate beam for radiotherapy treatment when variety of beam energies available. Evaluation of this type of characteristics will help to establish theoretical relationships between dosimetric parameters to confirm measured values of dosimetric quantities, and hence to increase accuracy in radiotherapy treatment.

Keywords: Radiotherapy, Treatment Planning, Photon beam, Absorbed Dose

INTRODUCTION

Determination of dosimetric characteristics of all radiation beams is vital so that most appropriate set of treatment planning parameters is chosen. Data on the percentage depth-dose of diagnostic X-rays are important in evaluating patient dose from medical exposure.[1] In radiotherapy, quality of a radiation beam is most usefully expressed in terms of its penetrating power, which is a function mainly of the mean photon energy, and may be fully described by its depth dose characteristics in water[2] but an increase in surface dose with field size is also noted due to electron scattering from intervening materials.[3]

Data on dose distribution are almost entirely derived from measurements in phantoms, and then are used in a dose calculation system devised to predict dose distribution in an actual patient.[4] These phantoms are tissue equivalent and are made by different materials and different methods.[5–7] The materials and methods of pattern of Phantoms can be diverse, but they all are mainly used as a dosimetric calibration phantom for both the photon and electron beams, in a linear accelerator, in the radiation therapy energy ranges.

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. This data is actually representing different physics characteristics of the machine, beam and its energies in the form of dosimetric quantities.

Physicists are always interested to obtain these parameters, first to use in radiotherapy treatment and second to evaluate and investigate physics of radiation beams.

Interaction of x-rays with matter is the major issue in medical physics in general and in radiotherapy physics in particular, as medical physicists are always interested in the dose absorbed by a medium. Radiation interaction with matter has been the subject of many literatures.[8–11] Absorbed dose is a quantity which is scientifically rigorously defined and used to quantify the exposure of biological objects, including humans, to ionizing radiation.[12]

Absorbed dose in the body is dependent on depth, field size, photon energy and Source to surface distance (SSD). Measurement of absorbed dose is made using water or any other equivalent media phantom, which is kept perpendicular on 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. The aim of our work is to analyse the change with depth to investigate attenuation of photon beam by some medium, and its ability to penetrate.

MATERIAL AND METHODS

We intended to explore Depth dose characteristics of diverse range of photon beam. Though absorbed radiation dose is measured in phantoms of different materials but water 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. The special supplement (on the central axis depth dose for photon) of British Journal of Radiology (BJR 25)[2] serves as a guiding protocol for radiotherapy practices. The Percentage Depth Dose (PDD), and Tissue Maximum Ratio (TMR) data in special supplement of BJR which was dedicated for central axis depth dose data for use in radiotherapy, presented after a long dosimetric practice. We analysed the data of 10×10–cm field size for different energies 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 analyse the average decrease in dose with depth.

An X-ray 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. There are several important points to locate on the depth dose, for example;

- The surface dose, or the dose at a depth of 0 cm,
- The dose at a depth of 10 cm, and
- The dose at a depth of 20 cm.

These values are different for different field sizes even for same energy and source-to-surface distance (SSD). Also these parameters are different for same field size when beam energy is different.

Similarly different depths can also be explored which gives a certain percentage of doses, like

- The depth of the maximum value of absorbed dose, d_{max}
- Depth of 80 % dose; d_{80}
- Depth of 50 % dose; d_{50}
- Depth of 10 % dose; d_{10}

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 that surface dose decreases with increasing beam energy and for any given beam energy increases with degradation of the spectrum towards the lower energies. 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 then using doses at certain depths.

In present work, we have compared the depth of maximum dose [d_{max}] with the depth of 50% dose [depth where dose fall half of its maximum value] to check the relative attenuation of different photon energies. Data from BJR supplement 25 have been used to analyse this variation. Photon energy ranges from 2 to 50 MV.

In Radiotherapy dosimetry, especially in photon beam depth dose analysis we first examine the surface dose, of a certain energy and field size. It increases with increase both in energy and field size independently. From here the attenuation, penetration and scattering of beam results in a unique value of absorbed dose which is a function of depth, field size, Source to surface distance, Beam energy and the absorbing material. Surface doses have been measured on a Varian Linear Accelerator 2100 C/D, in PTW MP3 water tanks, using farmer type ionization chamber.

RESULTS

The depth dose behaviour of photon beams in any medium can be evaluated with the help of different parameters, which exhibit the attenuation in its primary intensity. Usually the absorbed dose is described as Percent Depth Dose, which is a function of depth ***d***, field size ***r*** and Source to Surface Distance (SSD) ***f***, is as follows:

$$P(d, r, f) = 100.\left(\frac{f + d_m}{f + d}\right)^2 .e^{-\mu(d-d_m)}.K_s$$

K_s is the scattering component. This indicates the three governing rules of photon beam attenuation, inverse square law, exponential attenuation, and scattering component. This is why Percent Depth Dose uniquely varies with depth due to attenuation, with SSD due to inverse square law, and with field size due to scattering effect.

When x-ray beam enters in some medium, attenuation will definitely take place to decrease the intensity of the beam. In the above equation, attenuation coefficient (μ) contain the effect of energy as 'μ' has different values for different energy and the medium in which measurement of absorbed dose is made.

We have compared the depth of maximum dose and depth of 50% dose, for different beam energies. Difference between both depths was calculated, and it was noted that this difference increases with increase in beam energy of photon. Table-1 shows that 'd_{50}-d_{max}' is increasing with beam energy, but important point is that there is a divers mode of variation.

This difference can be better to view in the Figure-1, where the divergence in two curves can be seen for all the photon energies.

In Figure-1, the relative difference between d_{max} and d_{50} of photon beams of different energies is plotted. The gap between two curves seems to increase with energy to indicate a greater penetration. Less energy beam will be attenuated more then beam of higher energy. This relative attenuation analysis is helpful to analyse the beam attenuation, penetration and its ability to deliver the dose on specific increments of depth.

Surface dose data for 6 and 15 MV Photon beams, which we have measured in Shaukat Khanum Memorial Cancer Hospital & Research Centre, Lahore Pakistan is given in table 2, for five different field sizes. Combining this with BJR data, the dose build up can be examined.

Table-1: Depth of maximum dose and depth of 50% dose for Photon Beams of Different Energies

Beam Energy (MV)	Depth of 100% Dose (cm)	Depth of 50% Dose (cm)	d_{50}-d_{max}
2	0.4	11.2	10.8
4	1	13.9	12.9
5	1.25	14.5	13.3
6	1.5	15.6	14.1
8	2	17.2	15.2
10	2.3	18	15.7
12	2.6	19	16.4
15	2.9	20	17.1
18	3.2	21	17.8
21	3.5	22	18.5
25	3.8	23	19.2
35	4.5	24.9	20.4
50	5.3	27.2	21.9

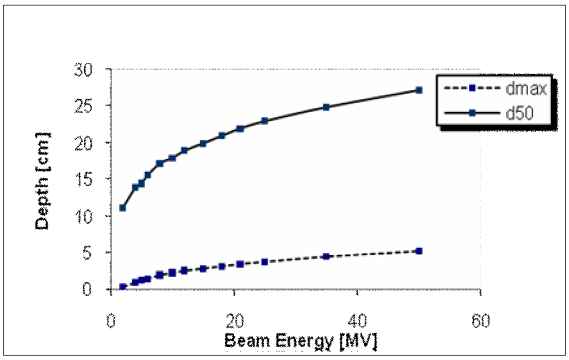

Figure-1: Depth of maximum dose and 50% dose, plotted against beam energy

Table-2: Surface Doses of 6 and 15 MV Photon beams for different field sizes

Side of the Square Field Size (cm)	6 MV (%)	15 MV (%)
10	52.4	28.5
15	55.1	33.9
20	58.6	38.8
25	61.3	43.4
30	64.4	47.6

Examination of dose fall off can also be made by the same procedure as for dose build up. We can evaluate the average decrease in the dose per cm. The decrease in dose can further compactly be checked if we collect and analyse the data which contain the depth of different percentage of doses, like that of 10, 20, 30 and 40% dose, but present data too can give the average decrease of dose with depth.

Table-3: Average decrease in dose in the depth between d_{max} and d_{50}

Beam Energy (MV)	d_{max} (cm)	d_{50} (cm)	Average decrease in percent dose [cm^{-1}]
2	0.4	11.2	4.63
4	1	13.9	3.88
5	1.25	14.5	3.77
6	1.5	15.6	3.55
8	2	17.2	3.29
10	2.3	18	3.18
12	2.6	19	3.05
15	2.9	20	2.92
18	3.2	21	2.81
21	3.5	22	2.70
25	3.8	23	2.60
35	4.5	24.9	2.45
50	5.3	27.2	2.28

It can be seen that average decrease in dose, between these two depths (d_{max} and d_{50}) decreases with increase in beam energy. Percentage dose for 2 MV photon beam reduces 4.63% per cm, but the same is 2.28% for 50 MV beam. The relationship between two energies is obvious, but the dose decrease rates do not have linear relationships. The reason is again the mode of interaction with matter. Higher energy beam interact with matter, with different attributes and hence its attenuation progression differ quite significantly from that of low energy beams.

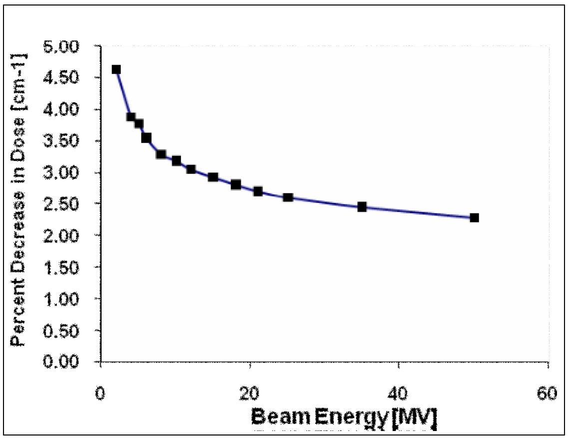

Figure-2: Average Decrease in Photon dose beyond d_{max}

Here beam energy is plotted against Percent Dose decrease per cm, and it can be seen, dose decrease is a function of energy. Higher energy beam have greater ability to penetrate and hence less attenuation is noted. Figure-2 is representing the average decrease in dose, in the region between d_{max} and d_{50}. An overall average can also be checked in this way. Average fall off of the dose decreases with beam energy. Although this may not be a precise approach to affirm the dose fall off, as dose do not decrease a certain value after every centimetre, or it do not decrease in continuous manner in the region between depth of maximum dose and depth of 50, 40, or 10%. Intensity of the incident beam starts to decrease soon after its emergence and it is significant after interacting with phantom material on its way. Intensity decreases continuously even in very small fractions of depth changes. Therefore an incident beam of certain energy, 15 MV for example is no more behaving like a beam of 15 MV energy after passing some centimetre distance in phantom. Its effective intensity changes and that change is governed by inverse square law, exponential attenuation and scattering factor.

DISCUSSIONS

The data of depth for maximum dose and 50% dose, for 13 beam energies (2–50 MV) is presented in Table-1. It is remarkable that all four columns contain sets of descending data to assure increase in depth of maximum dose, depth of 50% dose and difference between these two depths, with increase in energy of the photon beam.

The difference between depths for maximum dose and 50% dose increases with energy, showing relatively greater penetration (Figure-1). But this increase is not much as compared to the dose build up depth. The build up dose depth is apparently the depth of maximum dose, which is greater for high energy photon beams. If we wish to compare the dose build up with dose fall off, we will definitely need surface dose (dose at 0 cm depth) so that increase in dose per unit of thickness can be compared with decrease in dose per unit thickness beyond the Depth of maximum dose. Even the surface doses for most of the energies are not provided with the BJR data, but it is obvious that relative increase in dose is significant in proportion with the decrease and fall off beyond the d_{max}.

Measured values of surface dose for both photon energies, and five different field sizes are presented in Table-2. Surface dose for 15 MV photon (for field size 10×10 cm) is 28.5 % and the absorbed dose attain its maximum value on a depth of 2.9 cm. It confirms an average increase of 25 % dose per cm. similarly 6 MV Photon have a relatively greater surface dose, but smaller value of d_{max}.

Beams having higher energies vary in both surface dose and d_{max} values, because surface dose will decrease while d_{max} increases with increase in energy giving a relatively greater build up region but the concept is not numerically generalised for all energy values due to the relative importance of various types of interactions between photon and matter, which is strongly dependent on the energy of the photon beam.

The total mass attenuation coefficient (μ/ρ) is the sum of four individual coefficients:

$$(\mu/\rho) = (\tau/\rho) + (\sigma_{coh}/\rho) + (\sigma/\rho) + (\Pi/\rho)$$

(Total) (photoelectric) (coherent) (Compton) (pair)

The change in relative importance of individual interaction components with energy is shown in Table-4.

Table-4: Relative importance of photoelectric (τ), Compton (σ), and pair production (Π) processes in water[4]

Photon Energy (MeV)	Relative Number of Interactions (%) τ	σ	Π
0.01	95	5	0
0.026	50	50	0
0.060	7	93	0
0.150	0	100	0
4.00	0	94	6
10.00	0	77	23
24.00	0	50	50
100.00	0	16	84

These results show that the attributes of interaction of Photon beam vary with energy. For a typical value, like 4 MeV Compton interaction is 77 % while pair production component of interaction is only 6 percent. As energy increase from this value, Compton process decreases and pair production component of interaction increases. Due to different mechanisms of these fundamental interactions, depth dose characteristics of photon beams in water or any other material are not identical.

The outcome of this analysis is important in viewpoint to choose the appropriate beam for treatment when variety of beam is available. The tumour or the target volume is never a small point, so keeping in view the shape and volume of the target, and desired distribution of the dose in tumour, a beam having ability to deliver the dose closely matching with the desire distribution will be best choice to be used. Sometimes target volume is having organs at risk in close proximity, so it is important to keep them below tolerance. This type of case will demand some dose distribution spectrum containing some sudden fall off which will be giving the desired outcome.

CONCLUSION

Analysis of depth dose characteristics of photon is helpful in achieving an increased degree of accuracy in radiotherapy treatment planning. It is noted that energy of photon beam is the major element of uniqueness of absorbed dose at certain depth in tissue or equivalent material. Doses on certain locations can have different values due to other dosimetric consideration like field size and SSD, too, but the spectral and point to point distribution of the dose is the exclusive property of the beam energy. The detailed analysis of depth doses provides portions of depth containing a special range as well as behaviour 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. Each target volume along with its surrounding tissues require specific dose distribution, so the beam capable of providing that certain distribution, and having a behaviour to traverse desired dose delivery should always be selected for radiotherapy.

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