Romanian Reports in Physics, Vol. 66, No. 1, P. 212–222, 2014

COMPARISON FEATURES FOR PROTON AND HEAVY ION BEAMS *VERSUS* PHOTON AND ELECTRON BEAMS*

M. MIHAI[1], M. SPUNEI[2,3], I. MĂLĂESCU[3]

[1] Emergency County Hospital Craiova, Radiotherapy Clinic, Craiova, Romania,
E-mail: mya_mihai@yahoo.com
[2] Municipal Hospital Timişoara, Radiotherapy Center with High Energy, Timişoara, Romania,
E-mail: spunei_marius@yahoo.com
[3] West University of Timişoara, Physics Faculty, Timişoara, Romania,
E-mail: malaescu@physics.uvt.ro

Received April14, 2013

Abstract. Radiotherapy currently uses ionizing radiations to destroy DNA of the cancer cells. These cells lose their capacities to reproduce, leading to cellular death and the tumors destruction.

The increased incidence of cancer, easier access to new technologies and the failure of chemotherapy to provide a long-term local control, leads to the necessity to find new technologies to treat this disease.

Because in the radiotherapy with photon beams, the large dose out of the adjacent target tissues is a considerable inconvenient, the latest research technologies in the radiotherapy treatment are developed for the use of proton and heavy ion beams.

Using the dosimetric measurements, this paper presents the main characteristics of photon and electron beams used in radiotherapy today in Romania. These characteristics are determined using a specialized software program called Mephysto. By comparison, using the same software program, there are presented outstanding features of the depth dose distribution for simulated proton beam, with the energy equal to 225 MeV.

The obtained results could be used in future in Romania, both in clinical dosimetry, for analyzing the proton beams and in research centers for the development of new treatment techniques.

Key words: photon, electron, radiotherapy, heavy ions, proton beams.

1. INTRODUCTION

The physical and clinical dosimetry represents a highly important process in the medical act. The main purpose of dosimetry is to characterize the radiation beams in a unitary method in order to obtain reproductive values for treatment. The

* Paper presented at the 1st Annual Conference of the Romanian Society of Hadrontherapy (ICRSH 2013), February 21–24, 2013, Predeal, Romania.

dosimetry offers information regarding the quantity, quality and the dose distribution released by the useful beams in different geometries. The dosimetry measurements have been achieved using efficient measuring systems, according to already implemented protocols in the radiotherapy centers in the country.

Today, can be found working equipments which produce X radiations and high-energy electrons in the radiotherapy centers from Romania.

Recent studies [1, 2] have demonstrated the qualities of the beams using charged particles (carbon ions and protons) in the treatment of deep and resistant tumors. R.R. (Bob) Wilson has first introduced carbon ions and protons for radiotherapy treatments in 1946 [3].

The difference between the photons and heavy particles for medical purposes is given by the distribution of the dose in depth. For photons, if the released dose at different depth levels presents a growing zone at the input, also known as the build-up zone, for protons, the sudden increase of the dose takes place at the end of the range and is called Bragg Peak [4]. One can say there are two mirrored curves.

The fact that for protons, the input dose is small, protects the volume next to the tumor, after the tumor volume the dose being practically zero.

For photons, due to exponential decreasing of the dose beyond the build-up region, after the tumor volume, the dose is different from zero. Organs located near the tumor receive enough doses, which may lead to undesired effects.

In this paper, based on the dosimetric measurements, and using the Mephysto software program, we present the main characteristics of the photon beams and the electron beams used in radiotherapy today in Romania. By comparison, using the same software, we determined the important characteristics for a simulated proton beam.

2. EXPERIMENTAL SETUP

All measurements were performed at the Radiotherapy Center Timisoara using as radiotherapy unit the linear accelerator CLINAC 2100SC, produced by VARIAN. This type of medical linear accelerator generates high-energy photons of 6 and 10 MV and high-energy electrons of 6, 9, 12 and 15 MeV.

Relative measurements were performed using water phantom MP3, two identical semi-flex ionization chambers with sensitive volumes of 0.125 cm^3 and TANDEM dual channel electrometer all produced by the same PTW company. For absolute measurements we used a setup composed from thimble ionization chamber PTW Farmer type 30001 and universal dosimeter UNIDOS from same company.

The experimental data collected are then analyzed using an adequate software program called MEPHYSTO produced by PTW.

3. PERCENTAGE DEPTH DOSE (PDD): EXPERIMENTAL RESULTS AND SIMULATIONS

In this chapter, we present the percentage depth dose measured in a water phantom for the photon beams and the electron beams produced by our linear accelerator. We determined the characteristic parameters for these beams using the same software program that we employed to simulate the percentage depth dose distribution for high energy proton beam with energy equal to 225 MeV.

3.1. DETERMINATION OF CHARACTERISTIC PARAMETERS FOR PHOTON BEAMS

In external beam radiotherapy, determination of the Percentage Depth Dose is very important. This dosimetric function describes the overall effect of the interaction of photon beam with matter.

Percentage Depth Dose (PDD %) is defined as the ratio of the absorbed dose at any depth in water to the absorbed dose at a fixed reference depth, along the central axis of the beam, expressed as a percent.

The main parameters for describing the photon beams are:

1. Depth of maximum absorbed doze = $z_{\max}$ or R_{100} [cm]
2. Percentage Depth Dose = PDD (%)
3. Percentage Depth Dose at 10 cm depth = PDD_{10} (%)
4. Percentage Depth Dose at 20 cm depth = PDD_{20} (%)
5. Reference depth = z_{ref} (in cm)
6. Quality index : QI = $1.2661\cdot(PDD_{20}/PDD_{10}) - 0.0595$
7. Dose value at surface phantom = D_S%
8. Depth at which the absorbed dose is equal to 80% of the maximum dose = R_{80} [cm].
9. Nominal Accelerating Potential = NAP [MV].

In Fig. 1 are plotted our experimental values for the ratio of the absorbed dose in water at different depths and maximum absorbed dose to water (PDD) for photon beams with energies of 6 and 10 MV. These measurements were performed under the following conditions:

Source to Surface Distance (SSD) =100 cm.

Reference Field Size = 10×10 cm^2.

Table 1 presents the synthesis of the experimental values for the parameters characterizing the photon beams.

The output of the installation is an important quantity in physical dosimetry. This type of linear accelerator is designed to release radiations with a dose rate between 240 cGy/min and 320 cGy/min. The calibration of the therapeutic beam imposes the release of a dose of 1 cGy for 1 Monitor Unit, in reference conditions.

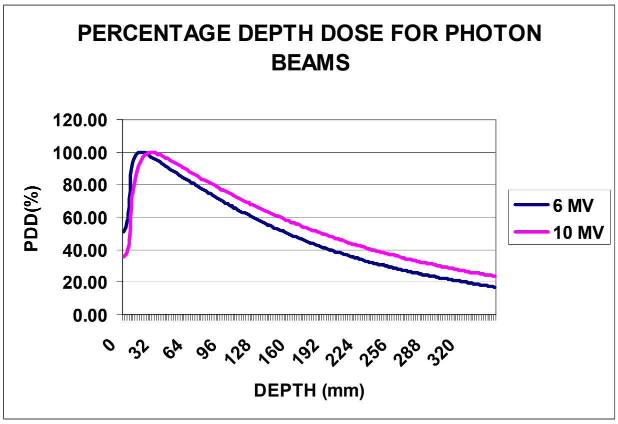

Fig. 1 – Percentage Depth Dose measured in water phantom for photon beams with energies of 6 MV and 10 MV produced by our medical linear accelerator VARIAN CLINAC 2100SC.

Table 1

Experimental values for the characteristic parameters of the photon beams produced by CLINAC 2100SC

Energy [MV]	$z_{max} = R_{100}$ [cm]	R_{80} [cm]	PDD_{10} [%]	PDD_{20} [%]	D_S [%]	QI	NAP [MV]
6	1.61	6.668	67.12	38.72	51.65	0.669	5.73
10	2.42	8.436	74.65	47.03	59.27	0.738	10.88

A Monitor Unit (MU) is a measure of machine output of a linear accelerator. Monitor Units are measured by ionization chambers, built into the treatment head of accelerator.

For determination of the output of linear accelerator in photon beam dosimetry, the experimental measurements are carried out under reference conditions accordingly to the recommendations of the international code of dosimetry [5].

The absorbed dose to water $D_w(z_{max})$ at the depth of maximum absorbed dose in SSD set-up [5] is calculated using the following relation:

$$D_w(z_{max}) = 100 \cdot D_w(z_{ref})/\mathrm{PDD}(z_{ref}) \ \ [\mathrm{Gy/MU}], \tag{1}$$

where $D_w(z_{ref})$ is the absorbed dose to water at the reference depth.

3.2. DETERMINATION OF CHARACTERISTIC PARAMETERS FOR ELECTRON BEAMS

Similarly as in photon case, the Percentage Depth Dose, PDD [%] is defined for electrons. The percentage depth dose in the water phantom shows a region of high and uniform dose at the beginning, followed by a rapid decrease to zero.

The electrons have a finite range in water, determined by the energy loss. Figure 2 depicts the graphs of the absorbed dose in water for electron beams produced by our linear accelerator CLINAC 2100 SC. The experimental conditions are: SSD =100 cm, reference applicator size = 10 × 10 cm^2, open field.

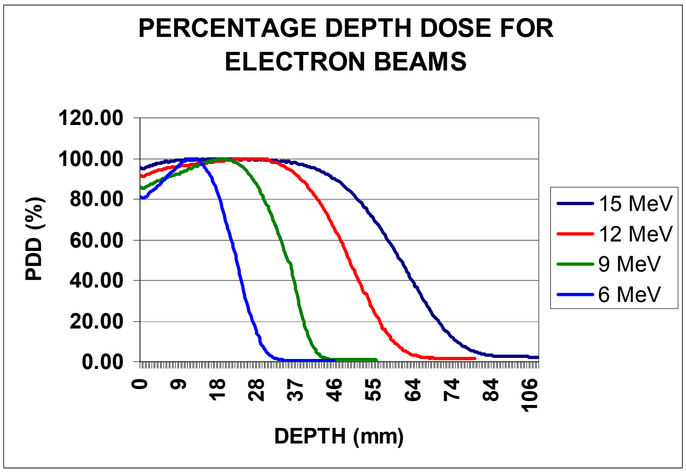

Fig. 2 – Measured Percentage Depth Dose (PDD) in water phantom for electron beams produced by our linear accelerator Clinac 2100SC.

To characterize the electron beams are defined the following quantities:

1. Depth of maximum dose value= R_{100} [cm] or [g/cm^2].
2. R_{50} is the half-value of the depth dose distribution in water. This is the depth in water (in g/cm^2) at which the ionization current is 50% of its maximum value. R_{50} is chosen as the beam quality index = QI [cm] or [g/cm^2]. The relations for R_{50} are [5]:

$$R_{50}\ [\text{g/cm}^2] = 1.029 \cdot R_{50,\text{ion}} - 0.06\ [\text{g/cm}^2] \quad \text{for } R_{50,\text{ion}} \leq 10\ \text{g/cm}^2 \tag{2}$$

$$R_{50}\ [\text{g/cm}^2] = 1.029 \cdot R_{50,\text{ion}} - 0.37\ [\text{g/cm}^2] \quad \text{for } R_{50,\text{ion}} \geq 10\text{g/cm}^2. \tag{3}$$

3. The mean energy at water phantom surface:

$$E_0 = 2.33 \cdot R_{50}\ [\text{MeV}]. \tag{4}$$

4. Practical Range, the depth at which the tangent plotted through the steepest section of the electron depth dose curve intersects with the extrapolation line of the background due to bremsstrahlung = R_p [cm].
5. Dose value at water phantom surface = D_S [%].
6. The mean energy at any depth z in water phantom is related by Harder equation:

$$E_z = E_0 \cdot (1 - z/R_p) \quad [\mathrm{MeV}], \tag{5}$$

where R_p represents practical range in water phantom.

7. Level of X-ray background = X-Ray Bck [%].

The reference depth used in dosimetric measurements is determined using the following formula [6]

$$z_{ref} = 0.6 \cdot R_{50} - 0.1 \quad [\mathrm{g/cm^2}]. \tag{6}$$

The values for these quantities are obtained from the Percentage Depth Dose measured for each of the energies produced by the linear accelerator, presented in Table 2.

Table 2

Experimental values for parameters characterizing the electron beams of medical linear accelerator Clinac 2100SC

Nominal Energy (MeV)	$z_{max} = R_{100}$ [cm]	R_p [cm]	R_{50} [cm]	D_s [%]	X-Ray Bck. [%])	E_0 [MeV]
6	1.23	2.86	2.26	80.50	0.67	5.41
9	1.88	4.31	3.47	85.41	1.09	8.20
12	2.58	5.99	4.92	91.43	1.94	11.58
15	2.02	7.46	6.16	95.51	2.94	14.44

One may observe that the electron beams have a finite range reaching up to 7.5 cm depth at 15 MeV energies. The maximum dose is distributed on 4–5 cm and after that depth, it rapidly decreases. These beams are used for tumors situated at few centimeters in depth.

The electron beams are not indicating for the treatment of tumors situated at depths that exceed the range.

The output determination for electron beams, in reference conditions, is similar to the one from the photon dosimetry. We use the practice code to determine the absorbed dose in water for electron beams [5].

Mathematical formula used to calculate the absorbed dose to water is conforming to equation (1), because only SSD set-up is used for electron beams.

Using the mentioned code of practice [5] we determined the relative errors between our monthly measurements over an entire year for photon and electron beams produced by our linear accelerator. The obtained results are presented in Table 3.

Table 3

The experimental values for output calibration, in reference conditions, for photon and electron beams produced by our linear accelerator CLINAC 2100 SC

Energy	PDD (z_{ref}) [%]	D_w (z_{ref}) [cGy/MU]	D_w (z_{max}) [cGy/MU]	Relative error [%]
6 MV	67	0.668	0.997	0.243
10 MV	73.21	0.735	1.004	0.461
6 MeV	96	0.967	1.006	0.695
9 MeV	99.8	1.006	1.008	0.841
12 MeV	99	0.997	1.007	0.722
15 MeV	98.3	0.990	1.007	0.697

We can observe that the relative errors are between 0.24% and 0.84%. All errors are smaller than 1%, which confirms the accuracy of our measurements. The permissible limit in determining the output for clinical use is ≤ 2%.

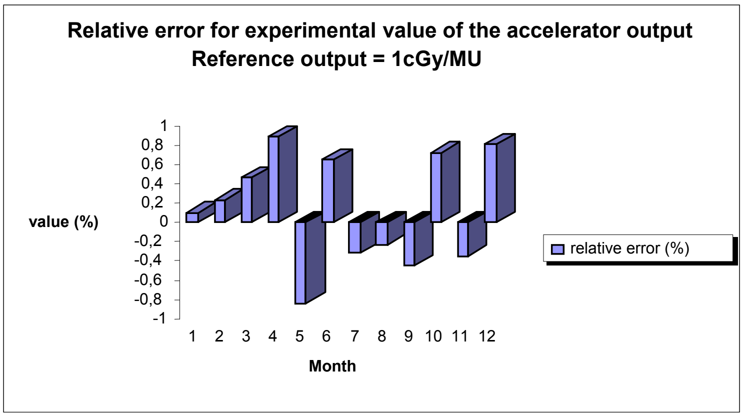

Fig. 3 – The output relative errors during the year 2012.

3.3. DETERMINATION OF CHARACTERISTIC PARAMETERS FOR SIMULATED PROTON BEAM

Proton therapy offers advantages over conventional radiotherapy, among which the most important are:

- A high conformal dose distribution in the planning volume.
- A high dose in the target volume.
- Steepest dose gradients between PTV (Planning Target Volume) and PRV (Planning Organ at Risk Volume).
- Reduction of integral dose to patient.

The Percentage Depth Dose provides information about proton beam parameters used in clinical dosimetry. The curve for a proton beam presents at the end a region where the absorbed dose in water rises to a maximum value, known as the Bragg Peak.

Clinical applications require a relatively uniform dose delivered to the volume to be treated. For this purpose, the proton beams have to be spread-out both laterally and in depth. This is obtained by the superposition of Bragg Peaks for different intensities and energies. This technique creates a region of high dose uniformity referred to as the Spread-Out Bragg Peak (SOBP).

Because protons have a finite range, like electrons, we define similar quantities to characterize the proton beam [5, 7]:

1. Maximum range, the depth of maximum dose value $= R_{\max}$ [cm] or [g/cm^2].
2. R_a and R_b [cm] represent the proximal and distal depths coordinates at which the absorbed doses match the defined percentage levels, in our case PDD level equal to 95% for both depths.
3. Reference depth is the value of the depth which is situated in the middle of the Bragg Peak or the SOBP = z_{ref} [cm] or [g/cm^2].
4. Practical range represents the depth at which the absorbed dose beyond the Bragg Peak or the SOBP falls to 10% of its maximum value = R_p [cm] or [g/cm^2].
5. Residual range represents the quantity: $R_{res} = R_p - z_{ref}$ [cm] or [g/cm^2], where z_{ref} is the depth of measurement and R_p is the practical range (both expressed in cm or g/cm^2).
6. The residual range R_{res} is chosen as the beam quality index = QI.
7. z_{ref} is the depth of measurement of the absorbed dose [cm] or [g/cm^2].
8. Peak Width is the positive difference between the coordinates R_a and R_b [cm].
9. Plateau level [%] represents a region where the dose increases slowly with depth. It is defined by the value of ratio between the absorbed dose at the first measuring point position equal to 0.0 mm and dose value at the point position equal to 100 mm.

Depicted in Fig. 4 is the Percentage Depth Dose for a proton beam with energy 225 MeV and 4×4 cm^2 field size. The curve from Fig. 4 is loaded from Mephysto software library and then analyzed using the previous methods used on photons and electrons beams.

The curve from Fig. 4 was determined in the following conditions:

Source to Surface Distance (SSD) = 270 cm.

Reference Field Size = 4×4 cm^2.

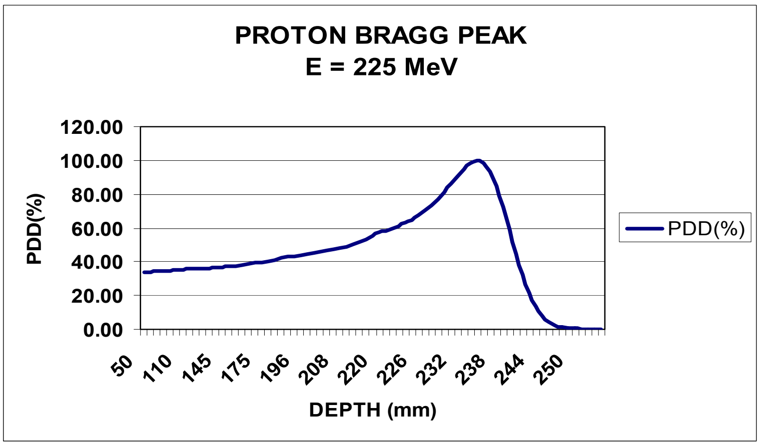

Fig. 4 – Depth dose distribution in water phantom for a simulated proton beam with energy 225 MeV.

In Table 4 are presented the numerical values obtained for the characteristic parameters of the simulated proton beam.

Table 4

The determined values for the simulated proton beam with 225 MeV, field equal to 4 × 4 cm^2

R_a [cm]	R_b [cm]	Z_{ref} [cm]	Peak Width [cm]	R_p [cm]	R_{res} [cm]	Plateau level [%]
23.29	23.66	23.48	0.37	24.46	0.98	34

One can observe from Table 4, the Peak Width of the simulated proton beam is small (0.37 cm) and cannot be used for the treatment of large tumors.

The SOBP for a modulated proton beam with the energy equal to 225 MeV and field size 18 × 18 cm^2 loaded from Mephysto, is depicted in Fig. 5. Spreading out of a Bragg Peak can be achieve by different modulation techniques, such as energy modulation or raster scanning or dynamic spot scanning [8].

The dose distribution presents a range limited by the proximal and distal distance, meanwhile the useful doses is distributes on a 10 cm domain (Fig. 5).

This feature is benefic for the treatment of large target volumes of 10 cm or more. As an undesirable effect, there can be observed that this technique leads to the increase of the dose at the input of the medium with up to 80%.

Table 5 presents the values for the parameters characterizing the Spread Out Bragg Peak (SOBP), which are determined using the available software.

We can observe from Tables 4 and 5 that the level of R_a on proton SOBP (Table 5) is shorter compared with R_a on proton Bragg Peak (Table 4). Also, the plateau level on proton SOBP (Table 5) is higher compared with Bragg Peak (Table 4).

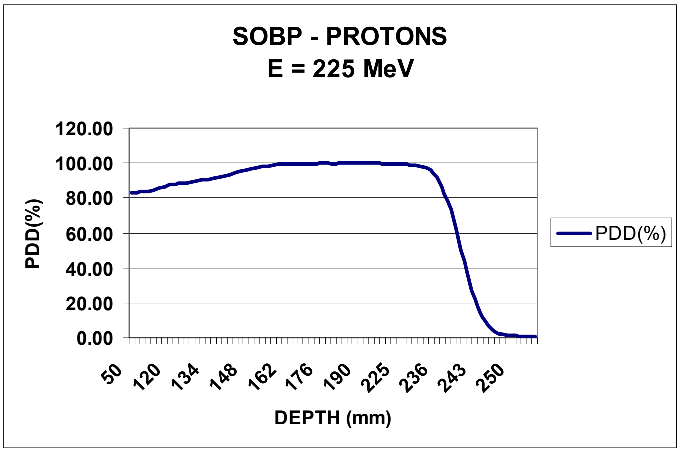

Fig. 5 – Percentage Depth Dose determined in water phantom for a simulated Spread Out Bragg Peak with energy equal to 225 MeV.

Table 5

The determinate values for a proton SOBP with energy 225 MeV

R_a [cm]	R_b [cm]	Z_{ref} [cm]	Peak Width [cm]	R_p [cm]	R_{res} [cm]	Plateau level [%]
15.571	23.519	19.05	8.95	24.48	5.43	83

4. CONCLUSIONS

All dosimetric measurements of photon and electron beams were performed in the Radiotherapy Center Timisoara using as radiotherapy unit the linear accelerator CLINAC 2100SC, produced by VARIAN.

Data analysis and determination of characteristic parameters of electron and photon beams were made using Mephysto software produced by PTW. Using the same software, we determined the characteristic parameters of one simulated proton beam.

The experimental results show that the dosimetric quantities used to characterize electron and proton beams are similar: z_{ref}, R_p, due to the finite particle path.

The obtained results show that the reference depth z_{ref} depends on the energy and the type of radiation beam used. Knowing the location of the tumor in the body, it can be chosen a specific type of radiation beam.

Starting from the percentage depth dose measurements in water phantom, we can achieve a unified characterization of radiation beams used in radiotherapy.

The dosimetry protocol [5] already used for electrons and photons beams can be used successfully in proton dosimetry.

The obtained results could be used in future in Romania, both in clinical dosimetry, for analyzing the proton beams and in research centers for the development of new treatment techniques.

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