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Determination of the attenuation coefficient for megavoltage photons in the water phantom

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Background: Attenuation coefficient (μ) plays an important role in calculations of treatment planning systems, as well as determination of dose distributions in external beam therapy, dosimetry, protection, phantom materials and industry. So, its exact measurement or calculation is very important. The aim of this study was to evaluate the μ in different points in the water phantom analytically as a formula, in addition to derive and parameterize it with dosimetry measurements data results. *Materials and Methods:* To find the attenuation coefficients at each point along the central axis of the beam in the phantom for every size of the fields, the first mathematical approach was performed for derivation of μs from percentage depth dose (PDD) formula. Then by dosimetry for different fields in different depths of water phantom, one can parameterize the obtained formula for μ in any field and depth. *Results:* By comparing the mathematical and dosimetry results, the parameters of the μ-expression were derived in terms of the dimension of square field in different depths. From this formula one can find the μ for any field in different depths for two energies of the Varian 2100CD linear accelerator, 6, 18MV with the statistical coefficient of determination of R^2>0.98. *Conclusion:* The measurement of the μ in each field size and depth has some technical problems, but one can easily measure the μ for every point of central axis of the beams in any field size. **Iran. J. Radiat. Res., 2012; 9(4): 251-255**

Keywords: *Radiation therapy, attenuation coefficient, dosimetry, megavoltage photons, varian2100CD.*

INTRODUCTION

The probability of all interaction processes between photons and atom is expressed with the linear attenuation coefficients μ (cm^{-1}), and it is obtained by the sum of all individual processes such as photoelectric absorption(τ), scattering(σ) and pair production(κ) (μ= τ + σ + κ) [1].

Furthermore, field shielding is accounted for in the treatment planning system (TPS) by considering the attenuation of the block to reduce the total dose under the shielded region [2]. As the X-ray beam has a continuous energy spectrum, it also suffers from change in quality with depth [3]. So the attenuation coefficients depend on the depth of the medium. Kleinschmaidt [4] provides a formal definition of the average attenuation coefficient , <μ>. In order to find a semi-analytical expression for μ, as a function of penetration depth (x), several functions were tested [5].

In addition, Monte Carlo codes such as DOSXYZ can be used to determine μs for narrow beams. This quantity depends on field size due to lateral equilibrium that becomes important in narrow beam geometries [6].

In several studies, the relationship between μ and atomic number of the medium or energy of the beam has been derived [5, 7-9] , but none of them reveals the relationship of μ with depth and field size simultaneously and analytically. In this study we made it possible to calculate μs in any depth and field size for two energies of the Varian 2100CD linear accelerator (i.e. 6 and 18MV).

MATERIALS AND METHODS

This work was carried out at the radiotherapy and oncology center in Golestan

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Hospital of Ahwaz, Iran. For the beginning a Scanditronix blue phantom (Wellhofer, Germany) (50 cm ×50 cm ×50 cm) was used for evaluating PDD of radiation fields 5×5cm up to 40×40 cm in any point of irradiated volume. A 0.13 ml ionization chamber (IBA, CC13, Germany) was used for the measurement. It was installed on the robotic moveable arms of the blue phantom, in a step by step procedure. Another ionization chamber was fixed on the head of radiation device as the reference chamber. The used radiation device was Varian 2100C/D accelerator (varian, USA) with two types of photon energy, 6 and 18 MV.

CU500E unit (Wellhofer, Germany) was used as computer interface to read the chambers' output from two different channels to control blue phantom arms. Omni-Accept pro 6.5 software (Wellhofer, Germany) was connected to the interface and used for collecting and recording data on the computer. As mentioned above, two chambers were used. The first chamber could move and the other was fixed on the head of the radiation device. The fixed chamber was placed out of the lines on which the moving chamber moved. The outputs were read by electrometer and then a ratio of these readings was used to make PDD or profile data.

As a mathematical point of view, one can write the following equation for the percentage depth dose of radiation in depth x, from the surface of the phantom (PDD_x). Because the attenuation coefficient (μ(x)) is variable with the depth

$$PDD_x \propto e^{-\int_0^x \mu(x')dx'} \qquad (1)$$

Differentiating from equation 1 with respect to the depth, $\mu(x)$ becomes:

$$\mu(x) = \frac{-1}{PDD_x}\frac{\partial PDD_x}{\partial x} \qquad (2)$$

As we know *PDD* depends mostly on the field size and the depth (when the SSD and Energy are constant), therefore $\mu(x)$ must be dependant to the field size too (i.e. $\mu(x, l)$). So, first, we had to find a formula for *PDD* to show the dependency on depth (x) and field size (l: length of one side of the square fields in centimeter).

Tahmasebi Birgani *et al.* [10] showed that there is a two-exponential relationship between *PDD* and x, so the equation would be like bellow:

$$PDD(x) = Ae^{-Bx} - Ce^{-Dx} \qquad (3)$$

If we have wanted to show the dependence of *PDD* to the field size we have to consider A, B, C and D as a function of l. we would have:

$$PDD(x,l) = A(l)e^{-B(l)x} - C(l)e^{-D(l)x} \qquad (4)$$

By comparing the experimental dosimetry data and the (eq.6) by Tblcurve2D software [11] (with $R^2>0.99$), the functional form of $A(l)$, $B(l)$, $C(l)$ and $D(l)$ can be obtained.

When we have the formula for $PDD(x,l)$, at last we can find the formula for $\mu(x, l)$ and that will be the attenuation coefficient for any depth and field size.

$$\mu(x,l) = \frac{A(l)B(l)e^{-B(l)x} - D(l)C(l)e^{-D(l)x}}{A(l)e^{-B(l)x} - C(l)e^{-D(l)x}} \qquad (5)$$

Statistical Validation

For statistical evaluation, Tblcurve2D software was used, which has 4 common goodness of fit statistics. The dimensions of the coefficients (A, B, C, D) were the same as that of μ (cm^{-1}).

In the following formulae descriptions, *SSM* is the sum of squares about the mean, *SSE* is the sum of squared errors (residuals), n is the total number of data values, and m is the number of coefficients in the model. *DOF*, the degree of freedom, is n-m. Coefficient of Determination (r-squared):

$$R^2 = 1 - \frac{SSE}{SSM} \qquad (6)$$

Degree of Freedom Adjusted Coefficient of Determination:

$$DOF.R^2 = \frac{(1 - SSE \times (n-1))}{(SSM \times (DOF - 1))} \qquad (7)$$

Fit Standard Error (Root MSE):

$$StdErr = \sqrt{\frac{SSE}{DOF}} \quad (8)$$

F-statistic:

$$F - stat = \frac{\frac{(SSM - SSE)}{(m-1)}}{\frac{SSE}{DOF}} \quad (9)$$

As a fit becomes more ideal, the R^2 values approach 1.0 (0 represents a complete lack of fit), the standard error decreases toward zero, and the F-statistic goes toward infinity.

RESULTS

By using the Tblcurve2D software on experimental dosimetry results, based on TRS398 protocol, one can parameterize the equation 6 with coefficient determination of R^2>0.99; and, therefore, the parameterization of the equation 7 will be done automatically. The functional form of *A*, *B*, *C* and *D* in terms of treatment field size *l* (in centimeter) was obtained by Tblcurve2D statistics as the following:

$$A(l) = a_1 + a_2 e^{-l/a_3} \quad (10)$$

$$B(l) = b_1 l^{b_2} \quad (11)$$

$$C(l) = c_1 + c_2 e^{-l/c_3} \quad (12)$$

$$D(l) = d_1 l^{d_2} \quad (13)$$

where the coefficients $a_1, a_2, a_3, b_1, b_2, c_1, c_2, c_3, d_1$ and d_2 for 6 and 18 MV photon beam tabulated with R^2>0.98 and listed in table 1.

Table 1. The values for the coefficients of the equations 10 to 13.

	6 MV	18 MV
a_1	109.9833	111.9358
a_2	7.1866	17.9063
a_3	24.3405	12.5161
b_1	0.0767	0.0506
b_2	-0.1528	-0.0953
c_1	42.7014	54.9529
c_2	67.3190	84.6025
c_3	27.9401	22.1451
d_1	1.7560	0.5857
d_2	0.0000	0.2100

Figures 1 and 2 show the variation of μ versus different depths and field sizes simultaneously for photon energies 6 and 18 MV, for Varian 2100CD linear accelerator.

Finally one can calculate the attenuation coefficient for some depths and field sizes from the equation 5 like the table 2.

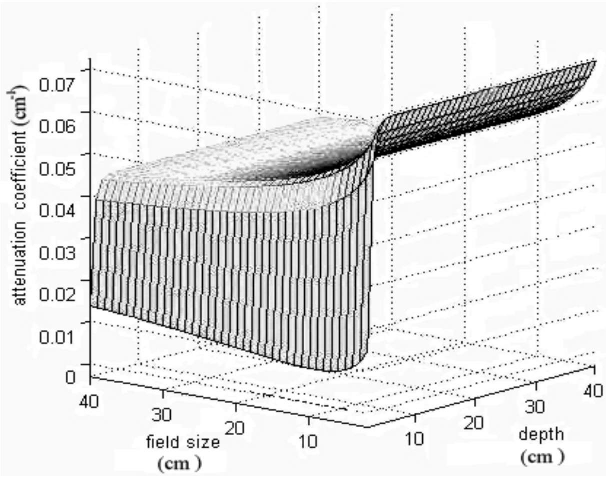

Figure 1.Variation of the attenuation coefficient versus depth and field size for 6MV photons of Varian2100CD accelerator.

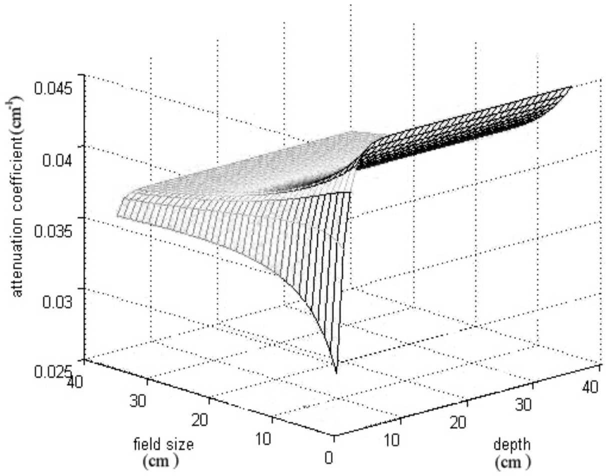

Figure 2. Variation of the attenuation coefficient versus depth and field size for 18MV photons of Varian2100CD accelerator.

DISCUSSION

In radiation therapy treatment planning, the attenuation coefficient in every points of the body for each field size should be assigned with or without blocks. Du Plessis *et al.* [6] worked on parameterization of the μs through the phantom with the

Table 2. The quantities of μ, for different depth and field sizes, for the two energies of the Varian2100CD linac.

Field Sizes (18MV / 6MV)	Depths: 4cm	6cm	8cm	10cm	12cm	14cm	16cm	18cm	20cm
5×5 (cm^2)	0.0086 / 0.0585	0.0367 / 0.0601	0.0423 / 0.0602	0.0435 / 0.0602	0.0437 / 0.0602	0.0438 / 0.0602	0.0438 / 0.0602	0.0438 / 0.0602	0.0438 / 0.0602
10×10 (cm^2)	0.0192 / 0.0526	0.0376 / 0.0541	0.0404 / 0.0541	0.0409 / 0.0541	0.0410 / 0.0541	0.0410 / 0.0541	0.0410 / 0.0541	0.0410 / 0.0541	0.0410 / 0.0541
15×15 (cm^2)	0.0240 / 0.0495	0.0374 / 0.0508	0.0392 / 0.0509	0.0394 / 0.0509	0.0394 / 0.0509	0.0394 / 0.0509	0.0394 / 0.0509	0.0394 / 0.0509	0.0394 / 0.0509
20×20 (cm^2)	0.0268 / 0.0474	0.0370 / 0.0486	0.0382 / 0.0487	0.0383 / 0.0487	0.0384 / 0.0487	0.0384 / 0.0487	0.0384 / 0.0487	0.0384 / 0.0487	0.0384 / 0.0487
25×25 (cm^2)	0.0284 / 0.0459	0.0366 / 0.0470	0.0375 / 0.0471	0.0376 / 0.0471	0.0376 / 0.0471	0.0376 / 0.0471	0.0376 / 0.0471	0.0376 / 0.0471	0.0376 / 0.0471
30×30 (cm^2)	0.0295 / 0.0447	0.0362 / 0.0457	0.0368 / 0.0458	0.0369 / 0.0458	0.0369 / 0.0458	0.0369 / 0.0458	0.0369 / 0.0458	0.0369 / 0.0458	0.0369 / 0.0458
35×35 (cm^2)	0.0302 / 0.0437	0.0358 / 0.0447	0.0363 / 0.0447	0.0364 / 0.0447	0.0364 / 0.0447	0.0364 / 0.0447	0.0364 / 0.0447	0.0364 / 0.0447	0.0364 / 0.0447
40×40 (cm^2)	0.0307 / 0.0428	0.0355 / 0.0438	0.0359 / 0.0438	0.0359 / 0.0438	0.0359 / 0.0438	0.0359 / 0.0438	0.0359 / 0.0438	0.0359 / 0.0438	0.0359 / 0.0438

existence of block or compensator, and defined the formulae for the μs in relation with depth, atomic number of the compensator, energy of the radiation and field size, differently [6]. However, we tried to give a novel formula for μ, without the existence of block, in relation with field size and depth of the treatment simultaneously. Of course, one could also parameterize the μ through the phantom for existence of the block in the same method. Moreover, the use of Monte Carlo simulation codes to get the PDD with or without block could be useful.

The μs were derived on the central axis. The values of these coefficients would change radically from the central axis in a real beam, since there was a change in the spectral properties of the beam partly due to the shape of the flattening filter and the angular distribution of bremstrahlung photon emerging from the target [12, 13]. Larson *et al.* [14] approximated the radial dependence of the effective μ for a lead filter with a linear function $\mu(r) = 0.0539 + 0.0005r$ (cm^{-1}) for a 4 MV beam. Bjärngard and Shackford [15] measured attenuation factors in water and found a quadratic dependence of the effective μ as a function of radius in water of the form $\mu(r) = 0.0473(1 + 0.00033r^2)$. This relationship was found for a 6MV open beam generated by a Philips SL75-5 linac. Thomas *et al.* [16-18] measured the radial variation of beam quality for 8 MV X-rays in water for a tungsten alloy filter. They found a linear relationship for effective μ expressed as a function of the azimuthal angle φ, between the central axis and the radial position on the surface of the water phantom. Their equation for the effective μ was $\mu = 0.037 + 0.020\varphi$. Apart from field size and to a lesser extent, depth dependencies, the effective μ was depended significantly, on spectral changes introduced off-axis by flattening filters.

In this study μ was derived for two different treatment X-ray beam energies and a range of beamlet sizes. It was found that after the 6cm depth, for 6 and 18 MV photon beams, μs decreased with the field size. Furthermore, it seemed that after the depth of 10 or 12cm the variation of the μ was negligible for both energies, As it can be seen the μs has decreased with the field size after the 4 or 6cm depth. This might due to the lateral electronic equilibrium that became less important in greater field sizes. It can be said that the dependence of the μs on the depth has been much weaker than that of the field size.

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