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Monte Carlo study on beam hardening effect of physical wedges

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ABSTRACT

▶ ***Original article***

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Background: Physical wedges are still widely used as beam modifiers in external beam radiotherapy. However the presence of them in the beam trace may cause beam hardening which may not be considered in many treatment planning systems. The aim of this study is to investigate the beam hardening effect generated by physical wedges via different beam quality indexes as photon spectrum, half value layer, mean energy and tissue–phantom ratio. ***Materials and Methods:*** The effect of physical wedges on the photon beam quality of a 6-18MV Varian 2100C/D accelerator was studied with the BEAMnrc Monte Carlo code. Good agreements were obtained between measured and calculated depth doses and beam profiles for open and wedged photon beams at both energies. ***Results:*** It was noticed that for 6 MV photon beams, physical wedges have more significant effects on beam quality than for 18 MV. Also it was obtained that at 18 MV photon beam as the wedge angle increased, the effect of wedge on beam quality becomes reversed and beam softening occurred. ***Conclusion:*** According to these results, it is recommended that beam hardening and softening of physical wedges should be considered in treatment planning systems in order to increase the accuracy in dose delivery.

Keywords: *Monte Carlo, beam hardening, physical wedge.*

INTRODUCTION

Irregular body contour and tumor volumes necessitate beam modifiers such as physical wedges to achieve a better uniformity of dose distribution (1-3). With the increasing interest in intensity modulated radiation therapy (IMRT), using of physical wedges has been reduced for field shaping. On the other hand, IMRT includes a small fraction of the overall treatment techniques for several reasons such as equipment capabilities, heavy maintenance program and labor burden. Thus physical wedges are still widely used as common intensity beam modifier devices in external beam radiation therapy (2, 5-7).

Radiation therapy relies on knowledge of the penetration of the beam into or through the patient; also the presence of a beam modifier as physical wedge in the beam trace changes the beam quality and makes some changes in the depth dose distribution which may not be accounted for many treatment planning systems (TPS) (3, 8-10). So complete knowledge of the dosimetric characteristics of beams is decretive in proper choice of particular wedge in clinical use (11). A number of practical parameters have been advised for specifying the x-ray beam quality such as photon spectrum, half-value layer (HVL), and mean energy. Recent dosimetry protocols recommend the use of tissue–phantom ratios (TPR) or percentage depth doses (PDDs) at a depth of 20 cm relative to the depth of 10 cm in a water phantom as an indicator of megavoltage beam effective energy or beam quality index (9, 12).

Beam quality indices are difficult to measure directly. Currently, Monte Carlo simulation is one of the most accurate methods to obtain information about the clinical beam especially in the unusual and complex situations such as presence of beam modifiers (as wedges) in the beam trace that can be measured hardly (4). A lot of studies were done on physical wedges but the properties of photon beams generated by linear accelerators may be varied between machine to machine and even for the same model (4, 13-16). In this paper the effect of physical wedges on x-ray beam quality with emphasis on beam hardening and softening points of view through different beam defining indices such as mean energy, HVL, spectrum and TPR20/10 by Monte Carlo BEAMnrc code is investigated.

MATERIALS AND METHODS

Monte Carlo Simulations

Monte Carlo simulations for open and wedged beams were performed using the BEAMnrc code which is based on the coupled photon-electron transport scheme of the EGSnrc code (17). In all calculations, the EGSnrc transport parameters were set as: ECUT= AE= 700 keV and PCUT=AP= 10 keV. Directional Bremsstrahlung Splitting (DBS) was used as a variance reduction method. The option of range rejection was also enabled and set to 1.5MeV.

The default parameters were employed for the PRESTA algorithm. The statistical uncertainties were better than 1%. This required up to 5×10^8 photon histories. One i5-2500k CPU@330 GHZ PC with 4 GB of RAM was used for this simulation.

The whole process of modeling was divided into two main parts: linac head simulation and beam hardening study.

Linac head simulation

The NRCC user-code BEAMnrc was used to simulate photon beams of 6 and 18 MV based on the realistic construction of Varian 2100C/D linac head (Varian Medical System). This code utilizes a series of component modules (CMs) for modeling each component of linac head that is consisted of SLAB, CONS3R, FLATFILT, CHAMBER, MIRROR and JAWS which were used for target, primary collimator, flattening filter, monitor chamber, mirror and secondary collimator, respectively.

BEAMnrc code outputs a phase space file including all the particle information. This phase space file is used as the input data or source for the depth dose calculations in water phantom (17, 18).

The information of electron incident on the target was obtained by trial and error using different electron-source configurations until to reach a best matching of the measured and simulated depth dose distributions and lateral beam profiles in water [19]. Percent depth dose curves and dose profiles at depth of d_{max} and 10 cm in water phantom for 10×10 cm^2 and 30×30cm^2 field sizes at a 100 cm SSD were simulated using another NRCC user-code, DOSXYZ. Approximately 4×10^9 particles were selected for transport with DOSXYZ. To analyze three dimensional dose distributions generated by DOSXYZ the interactive computer program, STATDOSE, was implemented. Calculated dose distributions in a water phantom were compared to measured one in order to check the simulation process.

At the next step, simulation of physical wedges with different angles of 15, 30, 45 and 60 were carried out in BEAMnrc code. Component module selected for physical wedges was PYRAMIDS which added to previous components in the linac head. In order to validate this step of simulation, calculated percent depth dose and beam profiles of different wedged beams for 6 and 18 MV were compared to those from measurements.

Beam hardening study

The other BEAM utility code, BEAMDP, was employed to analyze the phase space file obtained from simulations. Beam hardening due to physical wedge was studied in terms of beam quality index variations in different regions from the toe to the heel of the wedge. Beam quality indexes are as follows:

Photon spectrum: Complete specification of the beam quality requires knowledge of the spectral distribution, which means the amount of energy (energy flounce) present in each energy interval (9, 20). Spectral distribution is difficult to measure on clinical units; however, it gives the most rigorous description of beam quality (12). Monte Carlo is the only practical method to calculate spectral distribution (8, 9). Spectral distributions of open and wedged photon beams for both energies (6 and 18MV) were investigated at the central axis and off axis positions for the 10×10 cm2 field size by scoring the photon energy distribution across the field.

Mean energy: Another quantity that is often used for beam quality specification is the mean energy, defined as the ratio of the total particle energy to the total number of particles scored in spatial bin of equal area (12, 20). Mean energies were calculated for both 6 and 18 MV photon beams in the wedged direction.

Half-Value Layer (HVL): The beam specification through the HVL provides a general idea of the effective energy of the photon beam, which may be used to assess the beam penetration into tissue and to determine the appropriate values of the quantities used in dosimetry protocols (21). HVL is defined as the thickness, t, of absorber (water) required to attenuate the in air collision Kerma, K_C, to half of its measure from when no absorber was present. In order to calculate this thickness equation 1 is applied:

$$\frac{K_C(t)}{K_C(0)}=\frac{\sum_{n=i}^{N}\left(\frac{\Delta\varphi}{\Delta E}\right)E_i\frac{\mu_{en,air}}{\rho}(E_i)e^{[-\mu(E_i)_{absorber}t]}\Delta E_i}{\sum_{n=i}^{N}\left(\frac{\Delta\varphi}{\Delta E}\right)E_i\frac{\mu_{en,air}}{\rho}(E_i).\Delta E_i}=\frac{1}{2} \qquad (1)$$

The summation was performed over 200 equidistant energy bins, with fluence, $(\Delta\varphi/\Delta E)_i$, mid energy E_i, and energy width, ΔE_i. The linear attenuation coefficient, μ, and the mass energy absorption coefficient, μ_{en}/ρ, for each energy bin were taken from the XAAMDI database (22). To determine the HVL-values at heel, toe and central axis regions the photon fluences were scored in a square bin with 1cm width at corresponding regions.

Tissue Phantom Ratio (TPR): The parameter $TPR_{20,10}$ is defined as the ratio of doses on the beam central axis at depths of 20 cm and 10 cm in water obtained with a constant source to detector distance of 100 cm and a field size of 10×10 cm^2 at the position of the detector. The $TPR_{20,10}$ can be related to the measured $PDD_{20,10}$ using the following relationship:

$$\mathbf{TPR_{20,10} = 1.2661PDD_{20,10} - 0.0595} \qquad (2)$$

Where $PDD_{20,10}$ is the ratio of PDDs at depths of 20 cm and 10 cm for a field size of 10×10 cm^2 at the water phantom surface with 100 cm SSD (21).

Experimental Measurements: In order to validate the Monte Carlo simulations in this study, MP2-PTW field analyzer water phantom with 0.125 cm^3 PTW ionization chamber (PTW-Freiburg Germany) were used to measure depth doses and beam profiles for both wedged (with four different wedge angles of 15° and 30° made from steel, 45° and 60° made from lead) and open beams at two field sizes of 10×10 cm^2 and 30×30 cm^2. The transverse profiles were acquired in the water phantom at depths of d_{max}, and 10 cm for both 6 MV and 18 MV photon beams.

RESULTS

First the present Monte Carlo calculations for open fields and PWs were validated with the measurements, and then the beam hardening effects of PWs were investigated.

Validation of head simulation

The simulations for open beams were verified at first. For the Varian 2100 C/D, the electron incident energy and the mono-energetic beam FWHM to produce a dose distribution matched the measured one, were 6.1 MeV and 2.5 mm for 6 MV and 18.0 MeV and 2 mm for 18 MV beams respectively. It was found that the agreement between the simulations and the measurements were within 2%/2 mm for all the situations.

In order to validate the simulation of PWs Monte Carlo calculated PDD curves and profiles for 6 MV and 18 MV photon beams in a 10×10 cm^2 field size with 15, 30, 45 and 60° PWs were compared with the measments. The profiles were acquired at d_{max} and 10 cm depths (figures 1 and 2). Only the results for 10×10cm^2 field size are shown in this paper for visual clarity. These figures show that the Monte Carlo calculations agree well with the measurement within 2%/2 mm in the low and high gradient regions.

Beam hardening study

The photon energy fluence spectral distributions calculated by BEAMDP for 6MV and 18MV photon beams at 10×10cm^2 field size for 15, 30, 45 and 60° PWs are presented in figures 3 and 4. The spectra for the open field are also included. Photons were scored in air across the field at a plane 100cm away from the source and a 10×10cm^2 field size. It is clear that photon beams passing through PWs and open field are different. For both energies photon energy fluence was reduced in the wedged beams compared to the open ones. This effect is more significant with increasing the wedge angle.

The photons mean energy distributions calculated by the BEAMDP for 6 and 18 MV photon beams in a 10×10 cm^2 field with 15°, 30°, 45° and 60° physical wedges along with data for open fields are also illustrated in figures 5 and 6. From figure 5 it can be deducted that the mean energy for the PWs increases across the wedge direction compared to open fields. The larger wedge angle, the higher this effect. Also it is clear from figure 5 that mean energy is nearly uniform across the field at open beam but at wedged beams mean energy increases from the toe to the heel region across the wedge direction at all PWs. This effect is more significant at larger wedge angles.

From figure 6 the different results can be obtained. For 15 and 30 PWs, the mean energy increases from the toe to the heel region of wedges. But for 45 and 60 PWs this effect is not significant.

The beam hardening effect of the PWs at central, heel and toe regions of fields are further investigated in terms of HVL in figures 7 and 8. The results show that for the 6MV photon beam, with increasing wedge angle, HVL increases at all regions across the field along the heel, toe

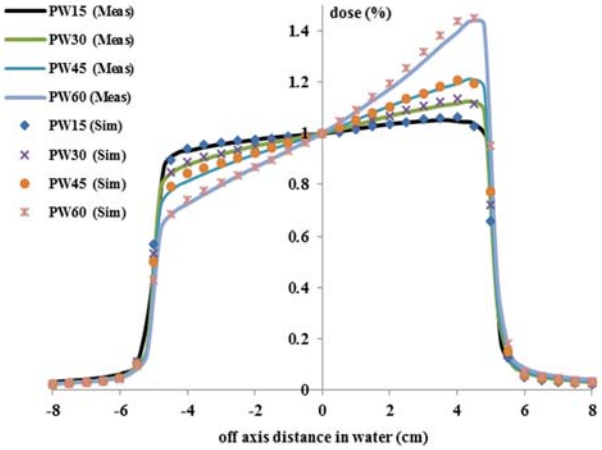

Figure 1. Comparison of the measurements and the Monte Carlo calculations of 15, 30, 45 and 60 PWs for 6 MV dose profiles at depth of d_{max} and 10×10cm^2 field size.

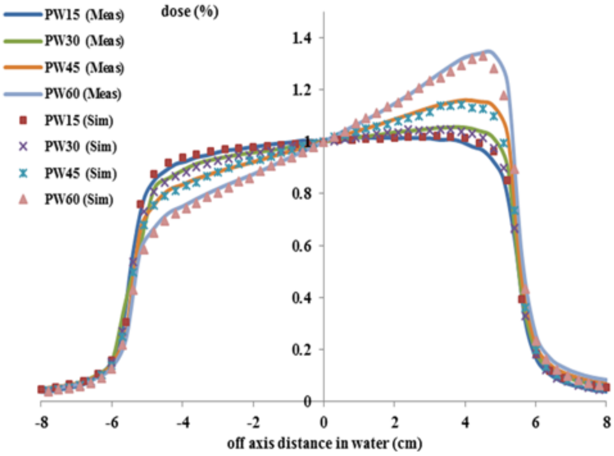

Figure 2. Comparison of the measurements and the Monte Carlo calculations of 15, 30, 45 and 60 PWs for 18 MV dose profiles at depth of 10 cm and 10×10cm^2 field size.

and the center. The HVL alteration is more significant at heel (12%) and less at toe (8%) regions which can be due to PW beam hardening effect. For the 18MV photon beams the results are different. From figure 8 it can be seen that with increasing the wedge angle from 0 to 30 degrees, HVL values increase across the field, which is pronounced lesser than 6MV photon beam. At higher wedge angles (above 30 degrees), the effect is reversed that means the HVL values decrease across the field. This effect is more significant at heel region.

The results of $TPR_{20,\ 10}$ values at three regions of field are summarized at tables 1. It can be seen that variations of $TPR_{20,\ 10}$ values at heel and center of field are significant for 6MV (above 10%). At toe region, $TPR_{20,10}$ for PWs are similar to open fields. These alterations ate not significant for 18MV.

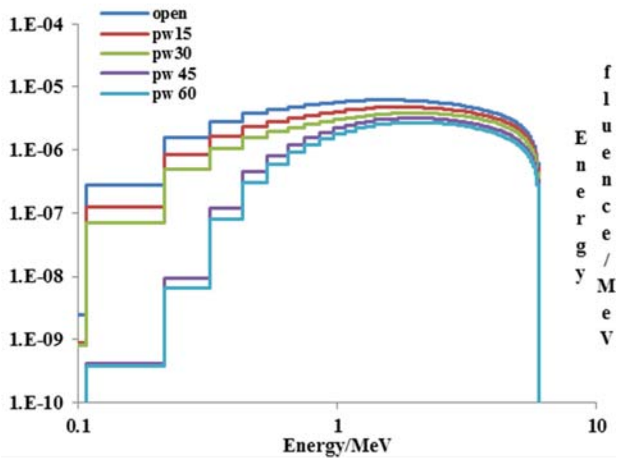

Figure 3. The photon spectral distributions calculated by the BEAMDP for a 6 MV beam in a 10×10 cm^2 field with15°, 30°, 45° and 60° physical wedges. The data for open field are also included for comparison.

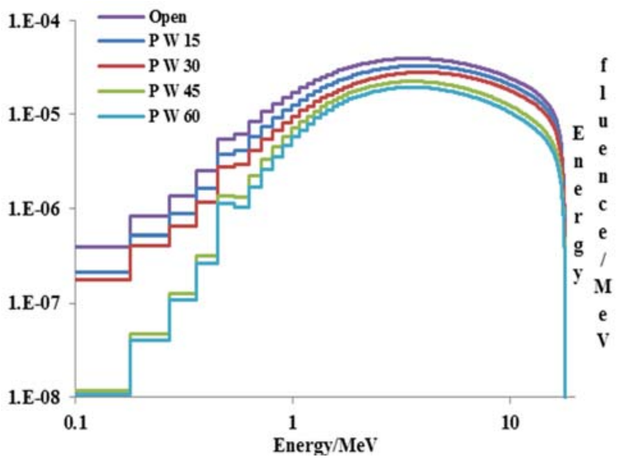

Figure 4. The photon spectral distributions calculated by the BEAMDP for a 18 MV beam in a 10×10 cm^2 field with 15°, 30°, 45° and 60° physical wedges. The data for open field are also included for comparison.

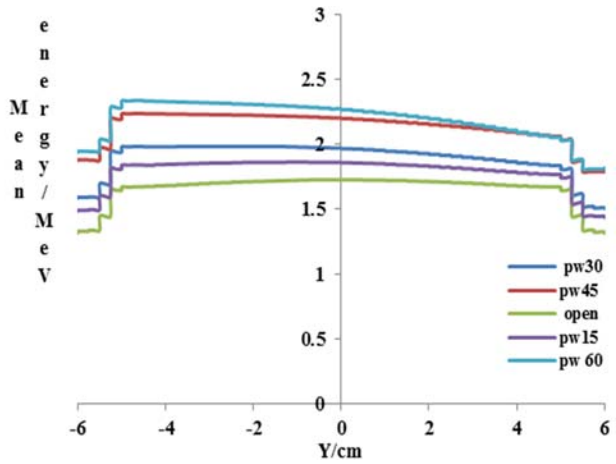

Figure 5. The photons mean energy distributions calculated by the BEAMDP for a 6 MV beam in a 10×10 cm^2 field in wedged direction with15°, 30°, 45° and 60° physical wedges. The data for open field are also included for comparison.

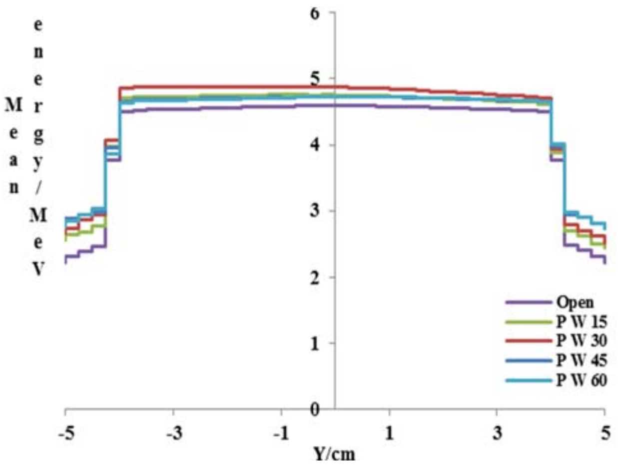

Figure 6. The photons mean energy distributions calculated by the BEAMDP for a 18 MV beam in a 10×10 cm^2 field in wedged direction with15°, 30°, 45° and 60° physical wedges. The data for open field are also included for comparison.

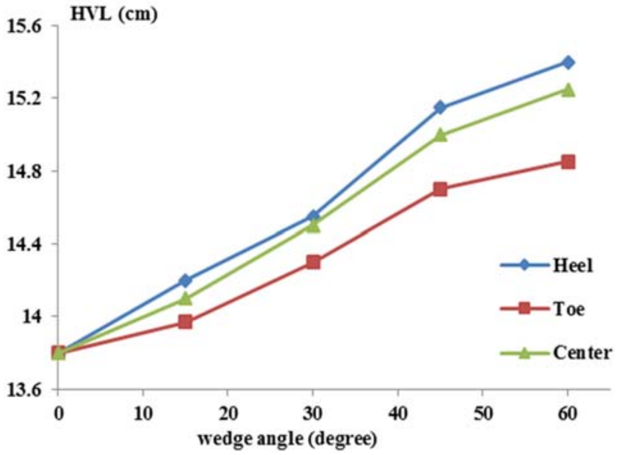

Figure 7. HVL variations with wedge angles at different off axis positions (Heel, Center and Toe) for 6MV photon beam.

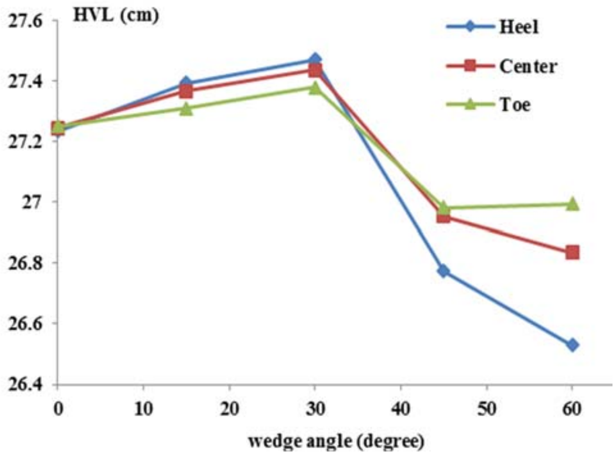

Figure 8. HVL variations with wedge angles at different off axis positions (Heel, Center and Toe) for 18MV photon beam.

Table 1. $TPR_{20,10}$ calculated for different PWs for 6 and 18MV photon beam.

6MV	Heel (wedge / open)	Central (wedge / open)	Toe (wedge / open)
PW:15	1.11	1.10	1.01
PW:30	1.23	1.10	1.00
PW:45	1.40	1.26	1.04
PW:60	1.57	1.25	0.95
18MV			
PW:15	1.00	1.01	1.00
PW:30	1.02	1.00	1.00
PW:45	1.02	1.01	0.98
PW:60	1.02	1.00	0.97

DISCUSSION

In general, excellent agreements (accuracy better than 2%) have been achieved between the Monte Carlo simulations and the measurements in lateral beam profiles and central axis dose distribution for open and wedged beams at both energies. These results are better than previously published results by other groups who simulated wedged beams generated by Siemens accelerator (8).

According to figures 3 and 4, PWs reduce photon energy fluence at both energies. This reduction is due to the presence of physical filters which attenuate lower energy photon beams and induce beam hardening. These results show the hardening effect is being increased with increasing the wedge angle. The beam hardening effect of PWs is responsible for the prominent difference in photon energy spectrum between open and wedged irradiation fields. These results are in good agreement with works done by Shih et al on 6 MV (23) and Momennezhad *et al.* on 9 MV wedged photon beams (4).

Results were shown in figure 5 are also in good agreement with photon energy fluence curves. Increasing the mean energy at wedge direction from the toe to the heel of wedged field can be attributed to the effect of PWs which absorb most of the low photon energies leading to hardening of photon beams. In other words, when a beam modifier like physical wedge is placed in the path of a photon beam, it attenuates the lower energy components of beam more strongly than the higher energy photons. So the mean energy of the photon beam will be increased. These results are found to be consistent with the results reported in the literature by others who investigated the effect of physical wedges on the photon mean energy distributions (1, 4, 23).

By comparison of figures 5 and 6 it can be seen that 6MV photon beam will be affected by PWs in a different manner to the 18MV photon beams. For 18 MV photon beam at 15 and 30 degree wedge angles, the mean energy increased but with increasing the wedge angle from 45 to 60 degree, the mean energy decreased. This later effect, known as beam softening can be attributed to the production of scattered photons from PWs. In fact, PWs filter lower energy photons and at the mean while produce low energy scattered photons. For higher energy incident beams such as 18 MV and wedges with larger angles (made from lead), the production of scattered photons may overcomes the filtering effect because of more contribution of pair production phenomena. These results are different from other studied who investigated the effect of internal wedge of GE machine on photon beam quality (15, 16). They found beam hardening of physical wedge at 6 and 18MV and beam softening at 25MV. These discrepancies can be due to the different mechanical positions of external and internal wedges in these two machines (i.e. GE and Varian). External wedge in Varian machine are placed between the secondary collimator and patient body while internal wedges in GE machine are mounted closer to the beam source between the monitor chamber and the upper jaws of the secondary collimators.

Similar results can be deducted from HVL curves at figures 7 and 8. Increasing of HVL values in figure 7 again implies beam hardening effect resulted from PWs and decreasing HVL values at 45 and 60 degree wedge angles in figure 8 is in agreement with the beam softening deducted from mean energy photon distribution at 18MV. These results are not consistent with Varatharaj studies who measured HVL for 6 and 18 MV photon beams of Varian Clinac-DHX linear accelerator passing through upper physical wedges (2). They found that HVL variations across the beam were significantly higher for 6 MV X-rays than for 18 MV X-rays and no reduction of HVL values was shown at 18 MV photon beams. These discrepancies may be attributed to different physical constructions of physical wedges and also their relative positions to the linear accelerator source which in turn made different dosimetric characteristics (2).

Variations of $TPR_{20,10}$ for PWs from table1 are also in good agreement with other indexes. As expected $TPR_{20,10}$ at toe region of field was not changed a lot because of low filtrations appeared at this part of fields. It can be seen from table 1 that variations of $TPR_{20,10}$ values are insignificant for PWs at 18MV. The reason of this is unknown. May be it can be attributed to the calculation of $TPR_{20,10}$ from equation 2.

From this study it can be emphasized that HVL values and mean energy distributions are suitable parameters to display the effect of PWs on the beam quality in a more accurate way. Dramatic variations of these parameters across the PWs field show the importance of considering the beam hardening and softening in calculation of TPS. Therefore TPS which implements these beam quality indexes at their calculations (using model based algorithms) are more accurate for wedged fields than others which don’t consider them in their calculations (using correction based algorithms).

CONCLUSION

From this study it can be concluded that the Monte Carlo simulation is a very useful method for investigation of physical wedges dosimetric characteristics. Our Monte Carlo results showed good agreement with measurements. Beam hardening and softening of the physical wedges change the photon beam quality parameters such as photon spectrum, mean energy, HVL, and $TPR_{20,10}$ index and because Monte Carlo is able to consider these changes, implementing of this method as a calculation algorithm in treatment planning system is recommended specially for wedged fields.

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