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Technical note

Accuracy checks of physical beam modifier factors algorithm used in computerized treatment planning system for a 15 MV photon beam

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ABSTRACT

In order to optimize the tumour dose by using wedge filters, systematic studies were carried out to investigate the accuracy of the beam modifier algorithm in a computerized treatment planning system (Theraplan plus, version 3.8). The effect of different parameters such as beam hardening and softening coefficients on the wedge factor was also studied. A 15 MV photon beam obtained from a linear accelerator was used throughout the experiments. Normalized wedge factors were determined experimentally as well as with the Theraplan plus system as a function of field size and depth in a water phantom for 15°, 30°, 45°, and 60° wedge filters. The attenuation coefficients, beam hardening coefficient, and beam softening coefficients were also determined experimentally using the 15 MV photon beam for each wedge angle. The measured normalized wedge factor was found to increase with increasing depth and field size for the 15 MV beam. The Theraplan plus calculated normalized wedge factor was found to be in good agreement with the experimental values. This study indicated that ignoring the dependence of the wedge factor on depth and field size will result in underexposure of the tumour.

1. Introduction

In order to have a uniform dose distribution within the target volume and to modify the dose distribution of a photon beam according to the body contour, beam modifiers (i.e. wedges) are commonly used in photon beam radiotherapy.[1–4] These wedges are made up of high-Z materials such as copper or lead. These are usually placed at an appropriate distance from the skin of the patient to avoid destroying the skin sparing effect of a megavoltage (MV) photon beam.[1,5,6] The wedge filters decrease the beam intensity and alter the beam quality when placed in the path of a radiation beam. The decrease in the beam intensity is taken into account in calculation of the treatment dose in terms of the wedge factor (WF), which is the ratio of doses at a reference depth with and without wedge under similar experimental conditions.[7,8] It is now an experimental fact that the WF depends on depth and field size; therefore, in order to deliver an accurate dose to the patient, it is desirable to determine its dependence on these factors.[5]

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The modified photon spectrum due to the presence of physical wedge filters may also be considered to achieve better accuracy in patient dose delivery.

A computerized treatment planning system (TPS) makes use of a combination of both hardware and software. The development of a feasible quality assurance program is essential to ensure that accurate and reliable dose distributions and associated calculations for external beam radiotherapy are produced.[7] Treatment planning is a multiple-step process. It is the responsibility of the medical physicist to maintain the proper functioning of the computerized TPS so that the proper treatment dose delivery is ensured.

Theraplan plus version 3.8, TPP (V 3.8), is an efficient treatment planning system that is used extensively in radiotherapy.[9,10] TPP (V 3.8) is based on a dose to energy-fluence concept utilizing a pencil-beam convolution model which is an internationally accepted dose-calculation method.[9,10] The absorbed dose is calculated by convolving pencil-beam kernels with the incident photon energy-fluence where physical quantities, estimated using conventional measured quantities, are used. For use of TPP (V 3.8), different input data are needed to enable it to create a dose distribution. The data required for use of TPP (V 3.8) include beam data, patient geometric data and machine specification. Beam specification includes modifier length, an attenuation coefficient, a hardening coefficient and two softening coefficients.[10] These parameters are used in the treatment planning system for calculating the variation in the wedge factors with depth and field size. When a photon beam strikes the attenuator, the low energy components are attenuated more strongly than the high energy components. As a result, the mean energy of the beam is increased. This is known as a beam hardening effect. This effect is accounted for by use of a beam hardening coefficient, which can be determined from the following equation[9,11]:

$$d' = d\,[1 - C_{hard} \times t\,(x)] \tag{1}$$

d' and d are the depths of the 50% dose without and with a wedge, C_{hard} is the hardening coefficient, and $t(x)$ is the thickness of the wedge at point x. C_{hard} can be determined by measurement of a tissue-phantom ratio or percentage depth dose curve with and without the wedge filter in place. Its value is usually positive and is less than 0.05.[11]

Many treatment planning systems overestimate the off-axis dose along the non-wedged direction; this overestimate is due to the beam softening effect which is more obvious at low energies, especially at shallow depths and extreme off-axis distances.[12,13] To take the beam softening effect into account, two beam softening coefficients, a_1 and a_2, are applied in TPP (V 3.8) if a beam modifier is used. The following quadratic equation can be used to calculate the off-axis linear attenuation coefficient μ, a_1 and a_2[9,11,13]:

$$\mu(r) = \mu(0)(1 + a_1 r + a_2 r^2) \tag{2}$$

where r is the off-axis distance, and $\mu(0)$ and $\mu(r)$ are the attenuation coefficient at the central axis and at off-axis distance r, respectively.[9,11,13] The formulation used by TPP (V 3.8) for calculation of the wedge factor $(\mathrm{WF})_\mathrm{P}$ is the narrow beam transmission through the thickness t_P of the beam modifying filter. It is given by[9]

$$(\mathrm{WF})_\mathrm{P} = e^{-\mu t_\mathrm{P}} \tag{3}$$

μ is the narrow beam linear attenuation coefficient for the radiation beam, which depends on the energy and the material of the beam modifier. At an off-axis distance, the attenuation coefficient is adjusted with the two beam softening coefficients to include the off-axis beam softening effect.[12]

From the above discussion it is clear that the idea of beam softening and hardening has been implemented in TPP (V 3.8). According to the TPP (V 3.8) requirement only the open beam data need to be put in and no wedged profile or wedge cross-section data are required to model the treatment unit. The user should only measure μ, C_{hard}, a_1 and a_2 and put in those values in TPP (V 3.8) which provide the best fit for the measured wedged profiles along both wedged and non-wedged directions. The aim of this study is to investigate the accuracy of the dose-calculation algorithm used in TPP (V 3.8) when wedge filters are used, as except for including the dependence of wedge attenuation on beam hardening and softening no other change in the dose-calculation algorithm is required.

2. Experimental work

The dependence of the WF on depth and field size was studied with an FC65 Farmer type ionization chamber attached to a Scanditronix-Wellhofer Blue Water Phantom with a positional accuracy of ±0.5 mm per axis and a reproducibility of ±0.1 mm for 15 MV photon beams produced by a Varian 2100C accelerator. Four upper external wedges with nominal wedge angles of 15°, 30°, 45°, and 60° were used in this study. For determination of depth dependence, both open and wedged beam data were taken at a constant field size (10 cm × 10 cm). For 2 cm to 22 cm depths, measurements were taken in steps of 2 cm and at 25 cm for an exposure of 100 monitor units (MU) at the rate of 320 MU/min for a 10 cm × 10 cm constant field size. In order to study the field size dependence, we made measurements at a fixed depth of 10 cm for 4 cm × 4 cm, 6 cm × 6 cm, 8 cm × 8 cm, 10 cm × 10 cm, 12 cm × 12 cm, 15 cm × 15 cm, 17 cm × 17 cm, 20 cm × 20 cm, and 25 cm × 25 cm field sizes at an exposure of 100 MU at the rate of 320 MU/min. The WF was then calculated with the help of the following formula:

$$\mathrm{WF} = \frac{D_w}{D_o} \tag{4}$$

D_w is the dose at a specified point along the central axis for a specified field size with the wedge in place and D_o is the dose at the same point in an open field of equal dimensions for the same time or the same number of MU.[6,7,14,15] This wedge factor is used in MU calculations in the case of linear accelerators to compensate for the reduction in beam transmission caused by the wedge. A normalized wedge factor (NWF) was introduced to circumvent the large differences between WF for different field sizes/depth. In the case of depth dependence, the normalization point was the depth at which the dose is maximum (2.9 cm for a 15 MV beam). For field size dependence, the normalization field size was 10 cm × 10 cm. To minimize errors in

Table 1 – Attenuation and softening coefficients for a 15 MV photon beam.

Wedge angle	Off-axis distance (cm)	Attenuation coefficient μ (cm^{-1})	Softening coefficient a_1 (cm^{-1})	Softening coefficient a_2 (cm^{-2})
15°	3.996	0.2488	0.00896	0.001522
	0	0.2347		
	−3.996	0.2320		
30°	4.005	0.2485	0.0044	0.000946
	0	0.2406		
	−4.005	0.2400		
45°	3.004	0.4993	0.00987	0.00305
	0	0.4723		
	−3.004	0.4713		
60°	3.005	0.5189	0.0169	0.00252
	0	0.4833		
	−3.005	0.4697		

the experimental values, data were obtained for two directions and the average of these measurements was taken as the WF.

In the computerized TPS, the required data were calculated according to the procedures and requirements of TPP (V 3.8).[10] For the measurement of beam hardening coefficients percent depth dose curve were obtained for open and wedged beam with the help of OmniPro-Accept software. The values of depth of 50% dose for open and wedged beams were used in Eq. (1) to calculate the value of C_{hard} for 15°, 30°, 45°, and 60° wedges. To calculate the total attenuation coefficients, open and wedged beam data, for known thickness of the wedge, at three different points in the radiation field, at the central axis and two points at off-axis positions, were obtained (see Table 1). These data were taken for 15°, 30° and 45° wedges at 20 cm × 40 cm radiation field sizes and for 60° wedge at 15 cm × 40 cm radiation field size. The total attenuation coefficients were calculated at these three positions by using the following equation[9]:

$$I_t = I_0 \exp(-\mu \times t) \tag{5}$$

where I_t is the beam intensity in the presence of a wedge in the radiation field, I_0 is the beam intensity at the same point in the absence of a wedge, and t is the thickness of the wedge corresponding to the measurement position. The two beam softening coefficients, a_1 and a_2, were calculated by entering the values of attenuation coefficients and off-axis distances (see Table 2) in Eq. (2) for 15°, 30°, 45°, and 60° wedges for 15 MV photon beams.

The variation in the WF with depth and field size was measured using a beam modifier factor algorithm in TPP (V 3.8). In the present work, the effect of C_{hard}, a_1, and a_2 on the WF was also studied. To do so, the variation in the NWF was calculated with and without C_{hard}, a_1, and a_2 in TPP (V 3.8). To get a clearer picture of the dependence of the WF on depth and field size for different wedge angles, we used the NWF. In the case of depth dependence for a 15 MV photon beam, the depth of the maximum dose (d_{max}) was the point of normalization for both experimentally measured values and TPP (V 3.8) calculated values. For field size dependence, 10 cm × 10 cm was the normalized field size in both experimentally measured and TPP (V 3.8) calculated values respectively.

3. Results and discussion

The attenuation coefficient (μ), beam hardening coefficient (C_{hard}), and softening coefficients (a_1 and a_2) were determined experimentally for each wedge angle for the 15 MV photon beam. Measurements were performed at the central axis and at two off-axis points, and μ, C_{hard}, a_1, and a_2 were calculated with the help of Eqs. (1), (2) and (3) for each wedge angle. The results obtained are given in Tables 1–2. The attenuation coefficients determined at the central axis and off-axis positions are not identical for the same type of wedge. This means that the beam quality at the central axis is different from that at off-axis positions.[7,8] An increase in the beam hardening coefficients was observed with increasing wedge angle for a 15 MV beam.

Fig. 1 shows the experimentally observed NWF as a function of depth at a fixed field size (10 cm × 10 cm) for a 15 MV photon beam. As may be seen in this figure, the NWF uniformly increases with depth and wedge angle.

Fig. 2 shows the experimentally observed NWF as a function of field size at a fixed depth of 10 cm for a 15 MV photon beam. As for the depth dependence, an increasing pattern has also been observed for an increase in the field size

Table 2 – Beam hardening coefficients for the listed wedges.

Energy	Depth of 50% dose (cm)				C_{hard}
	Wedge angle	Wedged field (d)	Open field (d')	Wedge thickness (t_w) (cm)	
15 MV	15°	20.37	19.98	0.76	0.025
	30°	20.44	19.98	1.41	0.016
	45°	20.17	19.98	1.26	0.007
	60°	20.17	19.98	1.63	0.006

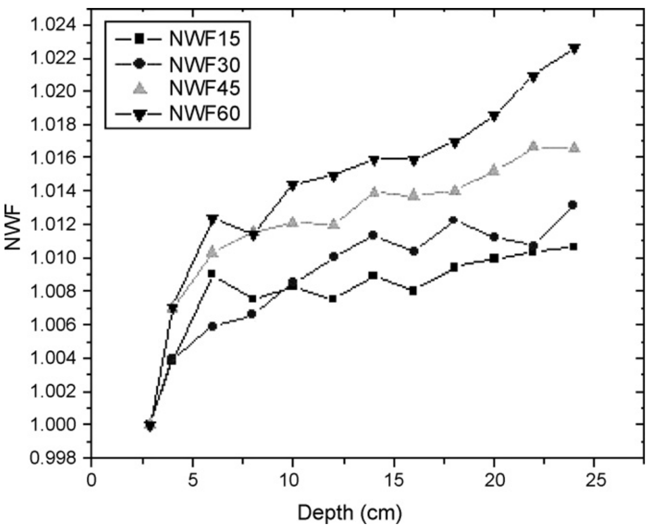

Fig. 1 – Experimentally observed normalized wedge factor (NWF) as a function of depth for a fixed field size (10 cm × 10 cm) for 15 MV photon beam.

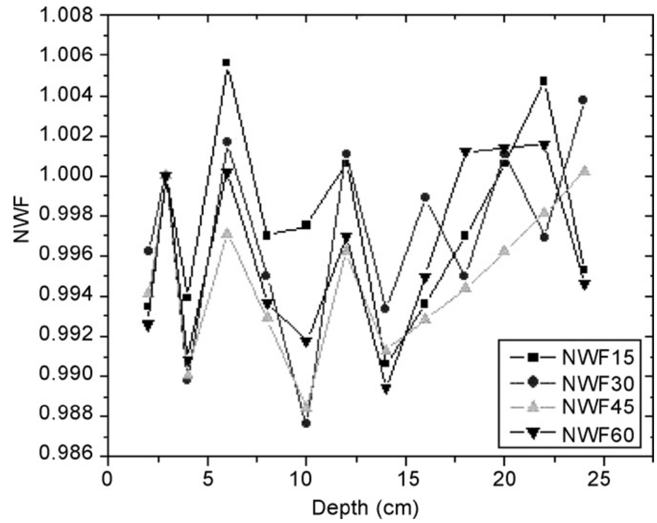

Fig. 3 – Calculated NWF as a function of depth keeping the field size constant (10 cm × 10 cm) for 15 MV photon beam using TPP (V 3.8) without incorporating C_{hard}, a_1 and a_2.

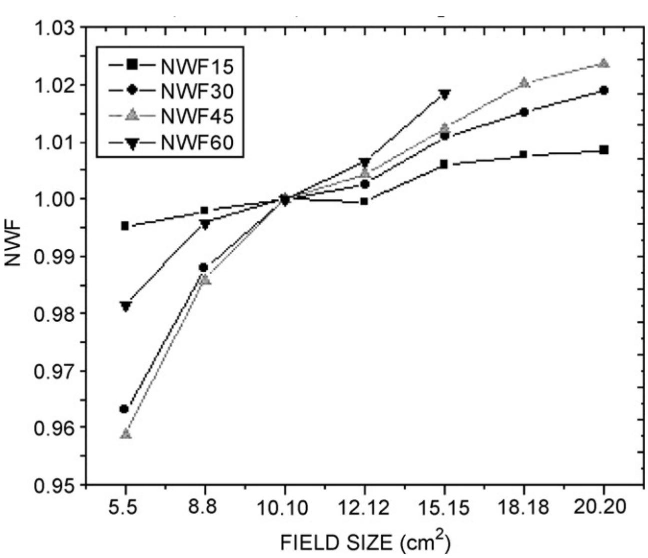

Fig. 2 – Experimentally observed normalized wedge factor (NWF) as a function of field size for a fixed depth (10 cm) for 15 MV photon beam.

and wedge angle. For field sizes ranging from 5 cm × 5 cm to 10 cm × 10 cm, the NWF increases from 0.1 to 0.22%, whereas for longer field sizes, there is a rapid increase in NWF values, which range from 0.1 to 2%.

Normalized wedge factors were also calculated by use of TPP (V 3.8) with and without incorporating the values of C_{hard}, a_1, and a_2 in the software, and they were compared with the experimentally measured values in our effort to study the effect of these parameters. The NWFs were calculated as a function of depth while the field size was kept constant at 15°, 30°, 45°, and 60° wedge angles for a 15 MV photon beam.

Fig. 3 shows the variation of NWFs, normalized at d_{max}, as a function of depth for a 15 MV photon beam. No clear pattern can be seen in this figure. The NWFs vary randomly as a function of depth.

Fig. 4 shows the TPP (V 3.8) calculated NWF as a function of field size keeping the depth constant (10 cm) for a 15 MV photon beam without incorporating the values of C_{hard}, a_1, and a_2. It is clear from the figure that the NWF (normalized at 10 cm × 10 cm field size) increases gradually with an increase in the field size.

Fig. 5 shows the percentage difference of the experimental and TPP (V 3.8)-calculated values with and without incorporating the values of C_{hard}, a_1 and a_2 as a function of depth, keeping the field size constant (10 cm × 10 cm) for a 15 MV beam. As may be seen in the figure, the TPP (V 3.8)-calculated values ignoring C_{hard}, a_1, and a_2 have an irregular pattern as compared to the experimentally measured values of the NWFs.

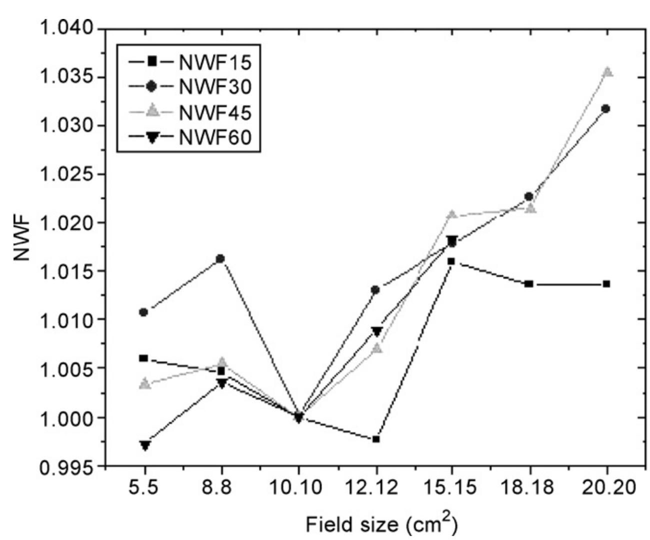

Fig. 4 – Calculated NWF as a function of field size keeping the depth constant (10 cm) for a 15 MV photon beam from TPP (V 3.8) without incorporating C_{hard}, a_1 and a_2.

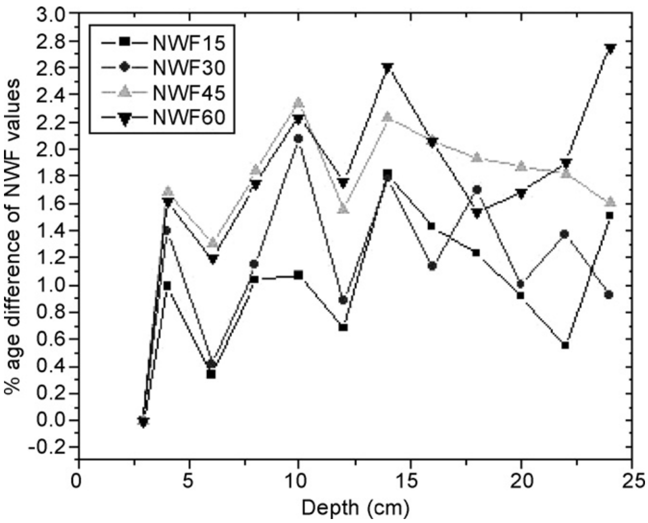

Fig. 5 – Percentage difference of the experimental and TPP (V 3.8) calculated values without incorporating C_{hard}, a_1 and a_2 as a function of depth keeping the field size constant (10 cm × 10 cm) for a 15 MV beam.

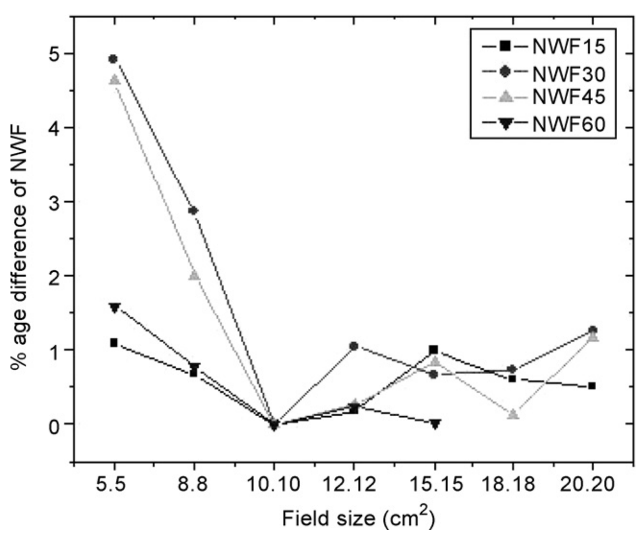

Fig. 6 – Percentage difference between experimental and TPP (V 3.8) calculated NWF values without using C_{hard}, a_1 and a_2 as a function of field size keeping the depth constant (10 cm) for a 15 MV beam.

The percentage difference is seen to increase with the depth for a 15 MV photon beam, and is larger for greater wedge angles. A maximum value of 2.75 of the NWF was observed at 24 cm depth for the 60° wedge.

Fig. 6 shows that the percentage difference of the experimentally observed NWF and TPP (V 3.8) algorithm as a function of field size is less than 1% for all wedges at all available field sizes for a 15 MV photon beam except for the 45° wedge, which differs by 1.5% at 20 cm × 20 cm field size.

Figs. 1–6 indicate that the WF depends on the field size and depth. The next step was to improve the modifier algorithm by incorporating the above factors in the computerized

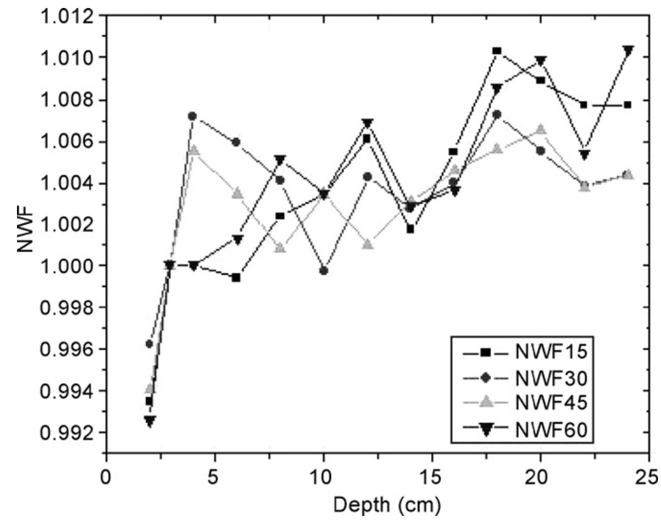

Fig. 7 – TPP (V 3.8) calculated NWF values as a function of depth keeping the field size constant (10 cm × 10 cm) using C_{hard}, a_1 and a_2 values for a 15 MV photon beam.

TPS in order to assure delivery of an accurate dose to the patient. In this context, beam hardening and softening coefficients (C_{hard}, a_1, and a_2) were determined experimentally (see Tables 1 and 2) and were fed into TPP (V 3.8). NWFs were again calculated for 15°, 30°, 45°, and 60° wedge angles as a function of depth, keeping the field size constant, for a 15 MV photon beam as given in Fig. 7.

Fig. 8 shows TPP (V 3.8) calculated values of NWFs plotted as a function of field size by use of the values of C_{hard}, a_1, and a_2 and keeping the depth constant for a 15 MV photon beam. The pattern of NWFs is seen to resemble the experimentally measured values for all wedge angles. The percentage difference of the modified TPP (V 3.8) values and experimental values were obtained and plotted on the same scale as those in Figs. 5 and 6. It is clear that this modification resulted in a reduction of the percentage difference by about 6.5%, 4.7%,

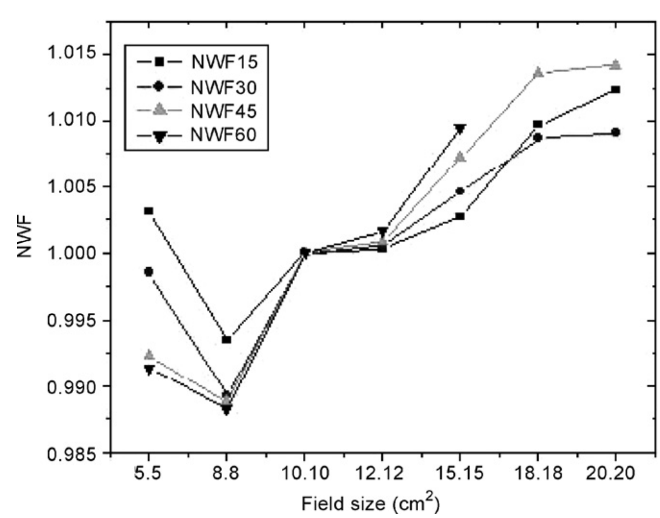

Fig. 8 – NWF as a function of field size keeping the depth constant (10 cm) for a 15 MV photon beam. TPP (V 3.8) was modified by incorporating the values of C_{hard}, a_1 and a_2 in it.

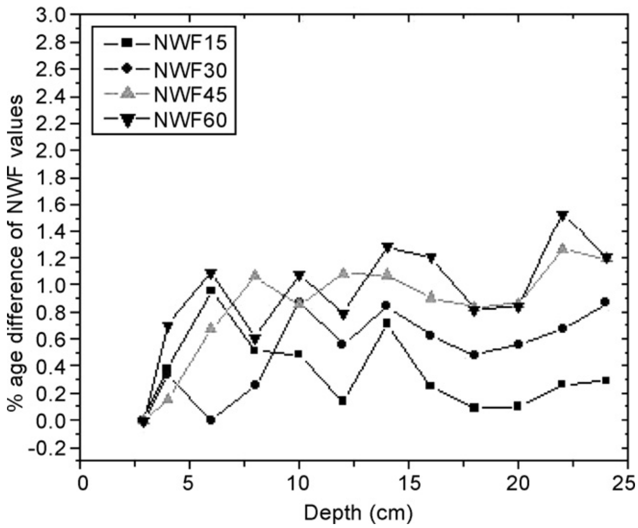

Fig. 9 – Percentage difference of the experimental and TPP (V 3.8) calculated NWF values incorporating the values of C_{hard}, a_1 and a_2 as a function of measurement depth keeping the field size constant (10 cm × 10 cm) for a 15 MV beam.

1.8%, and 1.8% for 15°, 30°, 45°, and 60° wedges at 24 cm depth for a 15 MV beam, respectively, as shown in Fig. 9. After incorporating the beam hardening and softening coefficients and improving the beam modifier factor algorithm of TPP (V 3.8), the field size dependence of NWFs was also investigated.

Fig. 10 shows the percentage difference among the NWFs calculated with the modified TPP (V 3.8) and experimental values as a function of field size. Comparing the percentage difference obtained with and without C_{hard}, a_1, and a_2 (see Figs. 6 and 10) it is clear that the percentage difference has been reduced considerably after modification of the TPS algorithm.

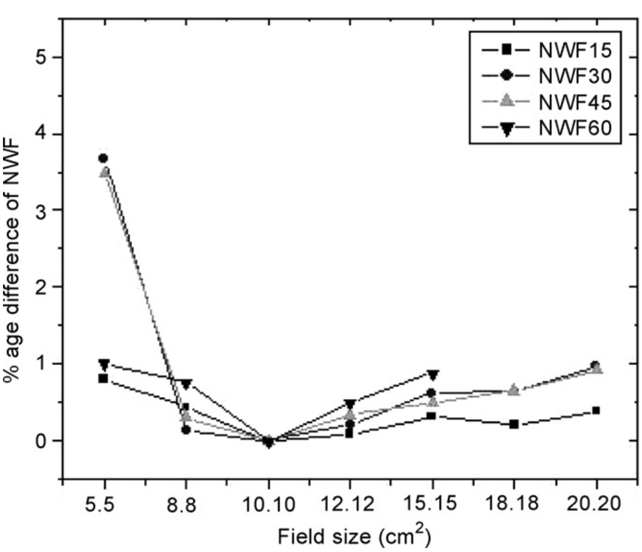

Fig. 10 – Percentage difference among the experimental and modified TPP (V 3.8) calculated NWF values as a function of field size keeping the measurement depth constant (i.e. 10 cm) for a 15 MV beam.

Similar increasing trends of calculated and experimental NWF values, plotted as a function of depth, have been observed which show that WF depends on depth.

The dependence of the NWF on depth is caused mainly by beam hardening and softening due to the presence of physical wedges, and is also due to the flattening filter. Beam hardening depends on the wedge material (Z-number) and beam energy. In this study, 45° and 60° wedges were made of lead, which has a higher probability for low energy photons to be attenuated than in the case of 15° and 30° iron wedges. That is why they cause significant variation in the NWF with depth. The NWF is also found to be field size dependent. This dependence is within 2.4% for a 15 MV photon beam (Fig. 3) for a 20 cm × 20 cm field size with reference to the normalized field size (10 cm × 10 cm). The increase in the NWF with field size is due to the non-uniform scattering of photons in the presence of the wedges. Scattering of the beam, which is one of the dominant factors, has already been reported in tissue compensators.[1] Another factor causing an increase in the NWF is the build-up factor. The build-up of the dose plays a significant role for broad-beam geometry, and hence, for larger field sizes, this factor dominates, increasing the NWF. In other words, the dependence of the WF on field size is mainly due to the change in phantom and collimator scattering. The percentage differences in the NWF as a function of depth are more dominant than the field size dependence. Ignoring the increase in the WF with depth will lead to underexposure of the patient.

Our results also indicate that the quality of the radiation beam plays a significant role in the calculation of the NWF. With every changing wedge angle, the hardening and softening of the beam varies, indicating the vital role of the wedge factor dependence of the dose. Thus, the quality of the beam itself is of significant importance in the dose precision.

4. Conclusion

To conclude, beam hardening (which is due to a flattening filter and physical wedge) and beam softening at off-axis locations are the main causes of the depth dependence of the wedge factor. The scattering of the photon beam in a phantom and non-uniform distribution of photon fluence due to the presence of the wedge are the main causes of the field size dependence of the wedge factor. The beam hardening and beam softening effects must be incorporated in the TPS if an accurate dose is to be delivered to the patient. Ignoring the beam hardening and beam softening effects will lead to underexposure of the patient. Therefore, it is recommended that the dependence of dose on the WF be considered in the treatment planning of radiotherapy patients.

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