A first order approximation of field-size and depth dependence of wedge transmission

Ramesh C. Tailor,[a] David S. Followill, and William F. Hanson
Department of Radiation Physics, The University of Texas M. D. Anderson Cancer Center, Houston, Texas 77030

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The Radiological Physics Center, through its dosimetry review visits to participating institutions, is aware that many institutions ignore the field-size and depth dependence of wedge transmission values. Reference wedge transmission values are normally measured by the Radiological Physics Center for a 10 cm×10 cm field at the calibration depth of 5 or 7 cm. Recently, additional measurements (1) for a 10 cm×10 cm field at 20-cm depth and (2) for a 20 cm×20 cm field at the calibration depth were included. The transmission under these two conditions was compared with that under reference conditions. The relative transmission values for 138 photon beams from 88 separate linear accelerators (4–25 MV) and ^{60}Co units were measured. Our data suggest that the dependence of the wedge transmission on field-size and depth, in the first approximation, depends on the absolute value of the transmission under reference conditions. For wedges with a transmission value greater than 0.65%, field-size dependence and change in depth dose are typically less than 2%. However, for wedges with transmission values less than 0.65%, field-size dependence increases with decreasing reference wedge transmission. The change in wedge transmission with depth is significant (>2%) only for photon energies less than or equal to 10 MV and can exceed 5% for thick wedges. Failure to include the depth and field-size dependencies of wedge transmission in patient dosimetry calculations can result in significant tumor-dose discrepancies. © *1998 American Association of Physicists in Medicine.* [S0094-2405(98)00502-1]

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I. INTRODUCTION

Since 1969, the Radiological Physics Center (RPC) has been funded by the National Cancer Institute (NCl) to provide quality audit of dosimetry practices at institutions participating in cooperative clinical trials supported by the NCI. One key component of the quality audit process is the review of an institution's dosimetry parameters during on-site dosimetry reviews. One parameter measured by the RPC is photon transmission through accessories such as trays and wedges.

Historically, wedges were used in cooperative group radiotherapy protocols to treat shallow lesions with small fields principally in the head and neck area and the breast. Therefore, the RPC measured wedge transmission (WT), only at the calibration depth of 5 or 7 cm for a 10 cm×10 cm field [WT(cal)] and used that measurement, i.e., WT(cal), to assess the institution's wedge transmission data.

As treatment techniques change and the cooperative groups propose new protocols, the RPC modifies its on-site dosimetry measurements to accommodate those changes. With the advent of the high-priority rectal studies, in which over 500 institutions participated, the use of large wedged fields to treat deep-seated tumors has resulted in the RPC modifying its set of WT measurements. A sampling of these rectal treatment records indicate that the average equivalent field-size is 16 cm×16 cm and the average treatment depth is 17.5 cm. Many of these rectal protocol patients (50%) received treatment with wedges ranging from 15 to 60 degrees and photon energies ranging from Co^{60} through 25 MV. Therefore, in order to investigate the magnitude of the field-size and depth dependence of WT and their impact on tumor-dose delivery, the RPC began collecting WT as a function of field-size and depth from a wide variety of linacs and photon energies in a systematic and reproducible manner. The data included the RPC's standard WT(cal) measurements, the WT for a large but clinically relevant field-size at the calibration depth and the WT for a reference field size at an extreme depth for a range of wedge angles.

This paper presents the results of a systematic set of measurements on wedges used on a large number of linear accelerators. We observe that, in the first approximation, the magnitude of the field-size and depth dependent effects are linear in the absolute value of the WT under reference conditions. We present data on how many institutions fail to account for these dependencies in their calculation of beam-on time. In addition, we show that the magnitude of the potential discrepancy in tumor-dose delivery when these effects are ignored can approach or even exceed 5%. Finally, we present suggestions as to how the practicing physicist can use these data in the clinic. Many institutions do not account for depth and field-size effects of WT. Quite often, institutions measure WT for the reference field-size at d_{max} depth, which is sometimes dictated by the treatment planning system. Some institutions account for the depth effect by using the wedge transmission value measured for the reference field-size at depth of depth-dose normalization in conjunction with the use of wedged depth-dose data.

II. MATERIALS AND METHODS

Wedge-transmission measurements were performed at over 56 institutions on 24 different models of therapy units using standard wedge filters provided by the manufacturers. The manufacturers include Varian (Varian Associates, Inc., Palo Alto, CA), Siemens (Siemens Medical Corp., Iselin, NJ), Philips (Philips Medical Systems Linear Accelerators, Shelton, CT), CGR-Orion (General Electric CGR USA/Orion Research, Inc., Boston, MA), Picker C-9 (Picker International, Inc., Cleveland, OH), and AECL (AECL/Theratronics International Ltd., Kanata, Ontario, Canada). Measurements were made on a total of 138 beams from 88 separate megavoltage therapy units. The photon energies ranged from ^{60}Co to 25 MV, and the wedge angles ranged from 30 to 60 degrees. The composition of the wedges included lead, steel, and brass. The WT measurement field-size never exceeded the maximum field-size allowed for the specific wedge.

Measurements were made in a water phantom using a Farmer-type 0.6-cm^3 ion chamber; NEL 2571, NEL 2505/3A, (Nuclear Enterprises, Ltd., Fairfield, NJ) or PTW N23333 (PTW/Nuclear Associates, Carle Place, NY)) read with a Keithley model 602 electrometer (Keithley Instruments Inc., Cleveland, OH). The long axis of the chamber was always perpendicular to the wedge plane. The calculated WT is the ratio of the average ionization with the wedge in place to the average open-field ionization. Two measurement techniques were used to assure precise alignment of the chamber and therefore precise transmission measurements. In the first technique, the ion chamber was precisely centered in the radiation field, using a 60-degree wedge, by requiring the ionization reading for a given irradiation time to be the same (within 0.3%) for two collimator orientations (180 degrees apart). The second technique used the measurement of WT for both collimator orientations (180 degree apart) and determined the average of the two measurements. All WT data were normalized to WT(cal), which was the central axis WT for a 10 cm×10 cm field at the calibration depth of 5 or 7 cm. With the exception of the Philips internal wedge, measurements with the wedge in place were performed by inserting the wedge in both orientations, i.e., heel in and heel out and averaging the measured values. To investigate the possible clinical limits of the field-size dependence and depth-dose effects, the WT for a 20 cm×20 cm field at the calibration depth of 5 or 7 cm and a 10 cm×10 cm field at a depth of 20 cm, respectively, was measured. The centering of the ion chamber in the radiation field was achieved independently at the 20-cm depth using one of the above techniques.

III. RESULTS AND DISCUSSION

Relative WT as a function of field size or depth is presented in Figs. 1, 2, and 3. The data are normalized to WT-(cal) so as to represent the change in wedge transmission and are presented as a function of the central-axis reference WT-(cal). In Fig. 1, data are included for all photon energies from ^{60}Co through 25 MV for wedges from 30 to 60 degrees. Data are not labeled with respect to energy because no significant energy dependence was seen. The open symbols represent the limited data we are able to obtain from previously published reports.[1,2] With the exception of one outlier,[2] previously published data lay within the spread of our measurement data. It is apparent that the WT for a 20 cm×20 cm field is larger than that for a 10 cm×10 cm field. More important than the fact of the increase is the clear trend seen when the data are plotted as a function of the reference trans-

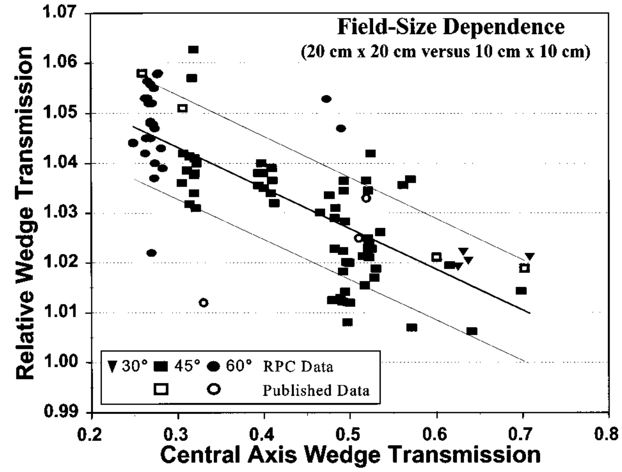

FIG. 1. Ratio of the central axis wedge transmission for a 20 cm×20 cm field to that for a 10 cm×10 cm field measured at the calibration depth (5 or 7 cm), plotted as a function of the reference wedge transmission for the 10 cm×10 cm field at the same depth. Data for 30-, 45-, and 60-degree wedges for the energy range from ^{60}Co through 25-MV x-rays are included. The solid symbols represent the RPC measured data, and the open symbols represent published data in references 5 and 6. The heavy solid line is a linear least-square fit to the data, and the light lines encompass ±1% of the fit.

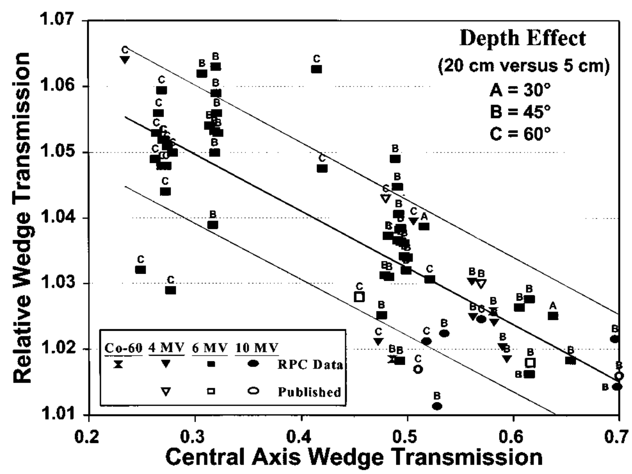

FIG. 2. Ratio of the central axis wedge transmission at 20-cm depth to that at calibration depth (5 cm) for a 10 cm×10 cm field, plotted as a function of the reference WT for the 10 cm×10 cm field 5-cm depth. Data from ^{60}Co through 10 MV x-rays are included for wedge angles from 30 to 60 degrees. The solid symbols represent the RPC measured data, and the open symbols represent published data in references 4 and 11. The heavy solid line is a linear least-squares fit to the data, and the light lines encompass ±1% of the fit.

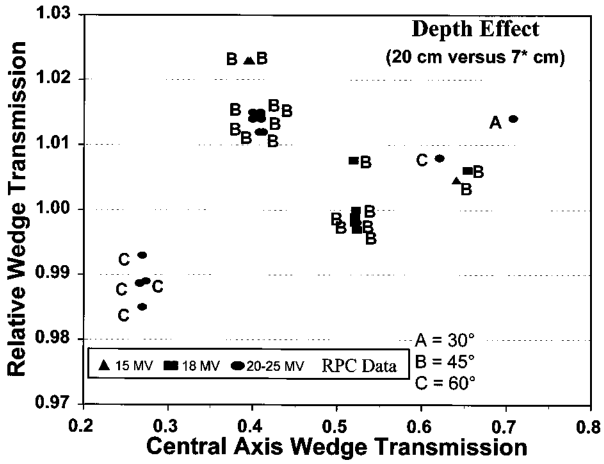

FIG. 3. Ratio of the central axis wedge transmission at 20-cm depth to that at calibration depth (7 cm) for a 10 cm×10 cm field, plotted as a function of the reference wedge transmission for the 10 cm×10 cm field at 7-cm depth. Data for 15–25 MV x-rays are included for wedge angles from 30 to 60 degrees. The 15-μV data have a calibration depth of 5 cm.

mission, WT(cal), irrespective of linac type, beam energy, or wedge composition. For transmission values near 0.3, the effect is approximately 5%, whereas for values of WT(cal) greater than 0.65, the effect is typically less than 2%. The dark solid line in Fig. 1 is a linear least-squares fit to the data. The thin solid lines represent $\pm 1\%$ of the fit. Even though the data appear to be scattered, approximately 80% of the data fall within this $\pm 1\%$ area, suggesting a standard deviation in the data of less than 1%. We reviewed three of the worst outliers carefully and found no fault with the data; we thus concluded that the spread and the outliers were real. Various authors[1–5] have made the generalized statement that as the wedge angle increases, the field-size dependence increases as well. More specifically, we propose that if one knows the wedge transmission under reference conditions, we can predict within $\pm 1\%$ at one standard deviation, the change in transmission for a 20-cm square field. Literature[1,6] attributes the field-size dependence primarily to the introduction of scattered-photon fluence by the wedges, which increases with the increase in field size.

Figure 2 shows the effect of depth on the measured WT for photon energies from ^{60}Co to 10 MV x rays. Wedge transmission measured at 20-cm depth for a $10\times 10\ \mathrm{cm}^2$ field, again normalized to WT(cal), is presented as a function of the absolute value of WT(cal). Data from previously published reports[5,7] are included as open data points. Again, the dark solid line is a linear least-squares fit to the data, and the thin solid lines represent a $\pm 1\%$ spread about the fit. Again, approximately 80% of the data were within the shaded area. A review of the major outliers again found no fault with the data. Sharma and Johnson[3] and McCullough *et al.*[7] have suggested that for energies equal to or less than 10 MV the depth dependence of wedge filters is significant ($>2\%$) only for 45- and 60-degree wedges at deep depths. However, our data quantifies the magnitude of the depth effect, dependent on the absolute value of WT(cal) which may or may not be related to the nominal wedge angle. Our analysis indicates that the depth dependence of the WT approaches or exceeds 5% for wedges with reference transmission near 0.3 and approaches less than 2% for reference transmission greater than 0.65.

TABLE I. The percent of visited institutions with a recommendation regarding wedge transmission values.

	Prior to January 1994	After January 1994
Percent of institutions with recommendations regarding WT	26%	70%

Figure 3 shows similar depth dependence data for energies greater than 10 MV. These data show no significant depth dependence ($<2\%$) or trend in WT for the high-energy beams as a function of depth. The relative wedge transmission values less than 1.00 as seen in the figure are result of beam softening[5,6] effect from very thick wedges at high energies.

It is commonly believed that the depth dependence of WT is due to beam hardening.[2,4,6–12] Kalend *et al.*[11] suggest that nearly half of the increase in the WT at depth comes from a second effect, dose-gradient scatter in the medium; however, Bar-Deroma and Bjärngard[6] argue that this effect is minimal. Because, we do not expect beam hardening of the wedged ^{60}Co beam, our ^{60}Co data points in Fig. 2 appear to support the hypothesis of Kalend *et al.*[11]

IV. USES FOR THESE GENERIC TRENDS

The WT data used by institutions to calculate beam-on time has always been a key concern of the RPC during its on-site dosimetry review visits. More institutions receive recommendations to review their WT values than any other dosimetry parameter. As seen in Table I, prior to January, 1994, when WT was measured only under their reference conditions, 26% of the institutions visited had a recommendation regarding WT. After January, 1994, when WT field-size and depth dependence measurements were added to our procedures, the percentage jumped to 70% of the institutions. These data suggest that although depth and field-size dependence of wedge transmission has been discussed at some length in the literature, approximately 50% of the institutions visited by the RPC still do not account for WT field-size or depth dependence, or both.

Data presented in Figs. 1 and 2 will allow institutions who have measured the wedge transmission under their reference conditions to estimate the expected change in WT with field-size and depth, and thus evaluate its clinical significance to their patients. In addition when field-size and depth dependence of wedge transmission is measured for the first time at an institution, the results can be compared with ours as a redundant check. Finally, we suggest that a simple test can verify whether a treatment-planning computer is properly accounting for depth effects. Ratios of point-dose calculations on the central axis with and without the wedge at the calibration depth of 5 or 7 cm and at 20-cm depth can be compared with an institutions measured data and/or with our data in Fig. 2.

V. CONCLUSIONS

The dependence of WT on depth and field-size has been shown in the first approximation to depend primarily on the absolute value of the transmission under reference conditions, WT(cal), independent of the beam energy, wedge composition, and linac type. The change is significant ($>2\%$) for wedge filters having central-axis transmission under reference conditions, ($10\ \text{cm}\times 10\ \text{cm}$ at 5 or 7 cm depth), less than 0.65 and it increases with decreasing WT(cal). The field-size dependence of a 20-cm^2 field relative to that of a 10-cm^2 field can exceed 5% for all energies from ^{60}Co through 25 MV. The change of WT with depth is significant ($>2\%$) only for photon energies less than or equal to 10 MV and can exceed 5% for thick wedges. There appears to be a significant number of institutions that do not account for one or both of the effects, i.e., field-size and depth dependence of WT. Failure to include the depth and field-size dependencies of WT in patient-dosimetry calculations can result in significant tumor-dose discrepancies. Several uses of these data in the clinic have been suggested. Regarding dynamic wedges, the RPC has very limited data and therefore their results are not included in this paper.

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[a]For correspondence: Tel: 713/792-3226, Fax: 713/794-1364, Electronic-mail: rpc@radonc.mdacc.tmc.edu

[1]J. R. Palta, I. Daftari, and N. Suntharalingam, ''Field size dependence of wedge factors,'' Med. Phys. **15**, 624–626 (1988).

[2]A. Niroomand-Rad, M. Haleem, J. Rodgers, and C. Obcemea, ''Wedge factor dependence on depth and field size for various beam energies using symmetric and half-collimated asymmetric jaw settings,'' Med. Phys. **19**, 1445–1450 (1992).

[3]S. C. Sharma and M. W. Johnson, ''Recommendations for measurement of tray and wedge factors for high energy photons,'' Med. Phys. **21**, 573–575 (1994).

[4]F. G. Abrath and J. A. Purdy, ''Wedge design and dosimetry for 25-MV x rays,'' Radiology **136**, 757–762 (1980).

[5]M. B. Podgarsak, S. S. Kubsad, and B. R. Paliwal, ''Dosimetry of large wedged high-energy photon beams,'' Med. Phys. **20**, 369–372 (1993).

[6]R. D. Bar-Deroma and B. E. Bjärngard, ''The relation between wedge factors in air and water,'' Med. Phys. **21**, 1043–1047 (1994).

[7]E. C. McCullough, J. Gortney, and C. R. Blackwell, ''A depth dependence determination of the wedge transmission factor for 4–10 MV photon beams,'' Med. Phys. **15**, 621–623 (1988).

[8]W. Sewchand, F. M. Khan, and J. Williamson, ''Variations in depth-dose data between open and wedged fields for 4-MV x rays,'' Radiology **127**, 789–792 (1978).

[9]A. Wu, R. D. Zwicker, F. Krasin, and E. S. Sternick, ''Dosimetry characteristics of large wedges for 4- and 6-MV x rays,'' Med. Phys. **11**, 186–188 (1984).

[10]A. M. Kalend and L. E. Reinstein, ''Dependence of wedge factor upon measurement depth,'' Med. Phys. **14**, 490 (1987).

[11]A. M. Kalend, A. Wu, V. Yoder, and A. Maitz, ''Separation of dose-gradient effect from beam-hardening effect on wedge factors in photon fields,'' Med. Phys. **17**, 701–704 (1990).

[12]J. R. Wiliiams and D. I. Thwaites, *Radiotherapy Physics* (Oxford University Press, Oxford, UK, 1993), pp. 64–65.