Relative electron beam measurements: Scaling depths in clear polystyrene to equivalent depths in water

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For purposes of mean incident energy determination and the accrual of consistent treatment planning data, measurements of relative ionization or dose made in clear polystyrene must be scaled in depth to produce depth-ionization or depth-dose curves equivalent to what would have been measured in water. Recommendations from various protocols for clear polystyrene to water depth scaling factors differ by as much as 5%. Here, central axis measurements of relative ionization as a function of depth have been made with parallel-plate chambers both in a popular clear polystyrene phantom of density 1.045 g/cm^3 and in water. Perturbation and displacement corrections were thus minimized. Both depth-ionization and depth-dose curves were formed for electron beams with nominal incident energies between 6 and 20 MeV and field sizes from 6 cm$\times$6 cm to 15 cm$\times$15 cm. Comparisons of the depths for 50% relative reading and practical range between the two phantoms yield average empirical scaling factors of 0.990 and 1.002, respectively.

I. INTRODUCTION

Most recent dosimetry protocols recommend electron beam dose calibration and dose distribution specification in water.[1-4] It is often more convenient or practical to make measurements in a solid phantom material such as clear polystyrene; a substance which is especially popular in the U.S.A. The protocols state that for absolute measurements made with an ionization chamber, one must scale the depth in polystyrene to an equivalent depth in water, and also correct the amount of charge collected for differences in electron fluences. For relative measurements, such as determinations of depth-ionization curves, depth scaling is the major concern. Here, a depth scaling factor SF is defined as the value by which the linear depth of measurement of a relative quantity in polystyrene, $Z(\text{poly})$, may be multiplied to obtain a linear depth in water, $Z(\text{water})$, with an equivalent relative reading;

$$Z(\text{water}) = \text{SF} \times Z(\text{poly}). \quad (1)$$

Any such SF will of course depend upon beam energy, angular spread, stopping power, and scattering power. However, use of a single value for beams of clinical importance would be convenient and may be practical.[2,5,6]

Several values of the clear polystyrene-to-water electron scaling factor have been proposed or adopted (Table I). Unfortunately, those suggested scaling factors differ by as much as 5% for clinical beams in the 6–30 MeV energy range. The AAPM Task Group 21 (TG-21) value (0.965) is based on theoretical derivations confirmed by measurements in clear polystyrene of density 1.04 g/cm^3 (Refs. 3 and 7). It differs markedly from the NACP value (1.018) derived from computations involving physical densities and effective atomic numbers[1,8,9] and the more recent ICRU values (1.027–1.007 for 5–30 MeV) computed[10] using formulations based on the continuous-slowing-down approximation. However, the results of recently published[6] and unpublished[11] measurements of ratios of practical ranges and depths of 50% dose in clear polystyrene phantoms of densities 1.041 and 1.05 g/cm^3 lead to experimentally determined scaling factors of magnitude less than unity (0.983 and 0.981, respectively).

Use of the extreme values for a clear polystyrene SF listed above would lead to differences on the order of 4 mm in the estimated water-equivalent depths of 50% dose for electron beams of approximately 20-MeV incident energy. While it may be argued that displacements of that magnitude have only minimal effects on the determination of dose at the calibration depth, due to use of different derived mean incident energies,[12] the displacements are clinically relevant in a geometric sense. The large variation in recommended values prompted the present investigation, including a reanalysis of previous measurements[13] and an expansion of them to include new data from a different machine. The results of careful measurements of ionization as a function of depth are presented for small volume parallel-plate chambers in water and in a popular clear polystyrene phantom. Empirical scaling factors are determined from comparisons of the depths of 50% ionization, 50% dose, and practical range derived from those curves.

II. MATERIALS AND METHODS

Both single- and dual-foil scattered electron beams from the Varian Clinac 18 and Clinac 1800 linear accelerators,[14] respectively, were used for field sizes of 6$\times$6, 10$\times$10, and 15$\times$15 cm^2, for nominal energies from 6–20 MeV. Thus,

TABLE I. Recommended values of the clear polystyrene-to-water scaling factor for 5- to 30-MeV electron beams.

Protocol	Scaling factor	Reference
NACP(1980)	1.018	1
AAPM(1983)	0.965	3,7
ICRU(1984)	1.027–1.007	4

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some combinations of field size and energy were investigated where the radius of the field size is less than the practical range of the electrons. Those situations were purposely included to provide checks under the clinical conditions where one ultimately wishes to characterize relative depth doses.

To maximize positional precision and minimize the need for corrections to ionization readings, small volume parallel-plate ionization chambers were used. In all cases, a chamber's flat surface was placed perpendicular to the beam central axis and the proximal surface of its air cavity was used as the effective point of measurement. At least 15 cm of material were always present behind each chamber to ensure that the electron beams were fully stopped in the phantoms. Temperature and pressure were monitored throughout the course of measurements and normalization runs at nominal depths of maximum dose were obtained at periodic intervals to insure the consistency of the data. Chamber bias polarity effects and ion collection efficiencies were checked for each chamber. Corrections applied to the raw readings were found to be either very small or negligible for the ion chambers, biases, and dose rates employed.

The water measurements were done using a NACP design parallel-plate ionization chamber available from Therados.[15] The chamber, as described by Mattsson *et al.*,[5] was specially designed for electron beam measurements. It was encased in a waterproof Lucite housing with a 0.1-mm-thick Mylar entrance window, and attached to the scanning arm of a Therados RFA3-50 water phantom/scanning system.[15] Ionization was collected using the RFA-3 preamplifier electrometer. The control unit has a stated resolution of 0.1 mm in position and 0.1% in normalized reading. For each data run, the chamber was always moved from a deeper to a shallower depth to eliminate backlash in positioning. This results in better than 0.2-mm precision in reproducibly positioning the chamber. A second 0.1-cm^3 thimble ionization chamber fixed in the corner of the radiation field was used as an independent monitoring chamber. Data were obtained under the control of a microcomputer.[16] The parallel-plate field detector was moved from its starting position, stopped, and held fixed at each data point, where readings of field current normalized to the monitor chamber current were averaged until they showed a variance of less than 0.2%. The chamber was then slowly and automatically scanned until reaching (1) a location 1 cm shallower in depth, or (2) a point receiving a test relative current reading with a 0.5% change from the previous data point, whichever occurred first. At that location, readings were again averaged and defined as another data point. All data obtained for the Clinac 1800 were measured using the automatic system. However, some of the earlier measurements on the Clinac 18 (Ref. 13), were made using an older continuous scan system which introduced an additional systematic uncertainty up to 0.5 mm in that small subset of the data.

Polystyrene measurements were made in a Nuclear Associates SCRAD design clear polystyrene phantom of density 1.045 g/cm^3 (Ref. 17). Depths in polystyrene were achieved by placement of additional slabs in front of the chamber. The thickness of each slab was measured with a micrometer. Data were obtained on the Clinac 1800 using a Capintec model PS-033 parallel-plate ion chamber[18] and on the Clinac 18 using a Holt–Memorial parallel-plate chamber.[17,19] Charge was collected with a Keithley 616 electrometer[20] for a given number of monitor units as measured by the machine's transmission chamber. Charge storage problems associated with cylindrical chambers in plastic phantoms[21–23] were not a problem here for the parallel-plate chambers and multiple slabs used, as evidenced by the agreement among measurements made at the beginning and end of each running period and on different days, in qualitative agreement with the findings by Thwaites.[6] Values of collected charge versus depth were entered into the computer in the same format used for the automatically collected water phantom data described above.

III. DATA REDUCTION

Computer data files of relative ionization $I'(Z)$ versus depth in phantom (of the effective point of measurement Z) were used as input for an interactive computer program written for analysis of electron depth-ionization curves in the spirit of recent dosimetry protocols.[1–4] All data were first corrected for divergence [source–surface distance (SSD) = infinity] using

$$I(Z) = I'(Z) \times [(\mathrm{VSD} + Z)/\mathrm{VSD}]^2 \qquad (2)$$

and renormalized.[4,24] The virtual point source-to-surface distances (VSD) were independently measured for each cone and energy by backprojection of the 50% beam widths measured at various distances in air with a small p-type silicon diode. The divergence corrections are made to remove any geometric field width dependence from the data for the comparisons of depth-ionization curves to follow, and to put the data in the format necessary for rigorous interpretation of the stopping-power data used to convert them to depth-dose curves.

By superimposing the ionization results from water and polystyrene (Fig. 1), one notices that particular values of percent ionization occur at slightly greater depths in polystyrene than in water, but that the differences are small. In order to more quantitatively define scaling differences, least-squares fits of straight lines were made to the data in the 60% to 30% falloff region and to the bremsstrahlung tail of each curve. To estimate random uncertainties in the measured quantities due to stopping the chamber for readings, electron beam fluctuations, small changes in chamber response, and the statistics of charge collection, data points immediately on either side of original 60% and 30% end points were also identified and used as end points for subsequent fits. Thus, an average slope and an average intercept, along with corresponding statistical standard errors, were determined for each curve. Depths of 50% ionization and their statistical errors were computed using the average fit parameters. The depths where those lines intersected lines fit to the bremsstrahlung tails were used as a measure of each beam's practical range.[4,24]

The average depths of 50% ionization computed above for each energy with the 15 cm × 15 cm field size in water were multiplied by the factor 2.38 MeV/cm to obtain mean incident energies.[25,26] Divergence corrected depth-dose

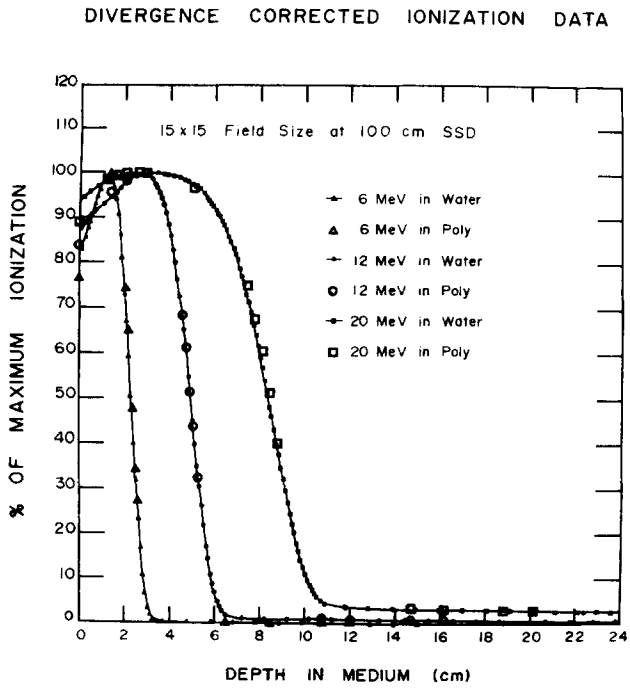

FIG. 1. Representative divergence corrected percentage depth-ionization curves in water (closed symbols plus lines) and clear polystyrene (open symbols). 15×15 cone at 100-cm SSD for beams of nominal energies 6, 12, and 20 MeV.

curves were obtained by multiplying the ionization reading at each depth times an appropriate phantom to air average stopping power ratio[1-4] and renormalizing each curve to 100% at its largest value. Again, only small differences were found to exist between companion curves (similar to Fig. 1). A more quantitative analysis of the dose data was also performed by making linear least-squares fits to regions of the curves as described above for the ionization data.

IV. ANALYSIS

For each combination of machine, cone size, and energy, a scaling factor (Eq. 1) was determined by computing the ratio of depth in water of 50% ionization, 50% dose, or practical range to the corresponding depth measured in polystyrene. Representative samples of values obtained from the ionization data are recorded in Table II. The results of the dose data comparisons are similar. The depths of 50% reading in water are consistently less than depths of 50% reading in polystyrene, but the practical range ratios are close to 1.00. This is in contrast to the ratio of relative densities, but in the same direction as other recent findings.[6,11] However, somewhat surprisingly, there appears to be no clear dependence on energy or field size. Weighted averages of ratios of depths of 50% reading and of practical range were taken over all machines, energies, and field sizes for both the ionization and dose data, with each individual ratio being weighted by the inverse square of its statistical uncertainty. They yielded average scaling factors of 0.991 ($\pm$ 0.003) and 0.988 ($\pm$ 0.003) from the $d(50\%)$ ionization and $d(50\%)$ dose data and values of 1.004 ($\pm$ 0.003) and 1.001 ($\pm$ 0.003) from the ionization and dose practical range data. That very similar values were obtained using the divergence corrected dose and divergence corrected ionization data is to be expected, as only relative readings are compared and the stopping power ratio between water and polystyrene remains fairly constant over the energy range studied.

The uncertainties quoted in the average values above are standard errors in those average values. As such, they incorporate random uncertainties in the determination of the sample mean values only. One standard deviation in the distribution of individual readings about those means will be larger by an amount approximately equal to the square root of the number of samples used in forming each average (30 here: two machines, three field sizes, five energies each; pointing to standard deviations of approximately 0.015 for the scaling factor distributions mentioned above). Additional systematic errors on the order of a few tenths of a millimeter may be associated with the initial positioning of the detectors. Those systematic errors, if present, would show up as constant overall displacements of unknown sign in the depths of 50% reading and practical range. However, their magnitude would be no larger than the statistical uncertainties quoted above.

It should be repeated that the scaling factors discussed here apply only to relative measurements such as determinations of depth-ionization curves. Other corrections, including multiplying the actual charge collected by proper electron fluence ratios, must still be performed to transfer

TABLE II. Representative ratios of physical depths of 50% ionization and practical range in water to corresponding physical depths in clear polystyrene for various field sizes and energies ($\pm$ estimated uncertainty).

	Nominal energy (MeV)	Cone size (cm×cm) 6×6	10×10	15×15
50% ionization	6	0.987(0.021)	0.987(0.027)	0.975(0.017)
	9	0.986(0.011)	0.986(0.011)	0.986(0.015)
	12	0.998(0.006)	0.996(0.007)	0.994(0.013)
	16	0.989(0.021)	0.989(0.028)	0.985(0.037)
	20	0.986(0.017)	0.984(0.032)	0.987(0.041)
Practical range	6	1.007(0.020)	1.007(0.025)	0.997(0.014)
	9	1.012(0.010)	1.012(0.010)	1.007(0.014)
	12	1.008(0.005)	1.012(0.006)	1.000(0.012)
	16	0.998(0.020)	1.000(0.027)	1.008(0.034)
	20	0.988(0.016)	0.998(0.030)	0.996(0.038)

TABLE III. Recent empirically determined clear polystyrene to water scaling factors.

Name	Scaling factor	Reference
Thwaites(1985)	0.983	6
Goede(1985)	0.981	11
This work	0.990–1.003	

absolute measurements from plastic to water. They have been described recently by various authors.[6,27–29] Preliminary measurements (not reported here) with the same clear polystyrene as above are consistent with electron fluence ratio corrections adopted by TG-21.[3]

V. DISCUSSION

Satisfactory alternatives to clear polystyrene for performing solid phantom electron dosimetry are emerging. Solid water[30] and especially electron solid water[31] appear to more closely mimic real liquid water and measurements done in them should require minimal corrections.[6] Those materials also appear to have a minimized tendency toward charge storage problems.[23] White polystyrene with approximately 10% titanium oxide has been found to be an effective water substitute,[32] and various types of it are common in Europe.[6] However, clear polystyrene is still quite popular in the U.S.A. and appropriate constants for its use should be maintained.

The recent TG-21 communication[12] rightfully pointed out that measurements in any plastic must be carefully assessed both due to differences in composition among plastics with similar names[33] and even what is meant by a single name such as polystyrene (white versus clear). They go on to suggest verification by the user of the scaling factor for any plastic used in electron dosimetry. Such measurements have been done here for a SCRAD-type clear polystyrene phantom similar to those found in many clinical departments. Experimentally determined scaling factors lie in between the values recommended by various protocols (Table I). However, these data and the results of other recent measurements (Table III) favor scaling factors with magnitude less than or equal to unity, but not as low as the value (0.965) currently recommended by the TG-21 protocol.[3] It would certainly be of interest for other comparisons of this sort to be performed on electron beams from other manufacturers and with other common commercially available clear polystyrene phantoms.

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