Practical methods of electron depth-dose measurement compared to use of the NACP design chamber in water

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Central axis relative dose versus depth measurements were performed using two different small volume thimble ionization chambers and a *p*-type silicon diode in a water phantom and with two parallel-plate ionization chambers, thermoluminescent dosimeters, and radiographic film in a popular clear polystyrene phantom. Values obtained were compared to the results of similar measurements in a water phantom performed with a plane-parallel ionization chamber designed and optimized for use in electron beams by the Nordic Association of Clinical Physicists (NACP). The NACP chamber is expected to minimally perturb the electron fluence and be least prone to point of measurement uncertainties. Its use in a water phantom closely approximates the spirit of recent international protocols. Data were obtained for the foil scattered electron beams generated by two different accelerators for field sizes from 6 cm × 6 cm to 25 cm × 25 cm and energies between 6 and 20 MeV. Easily identifiable effective points of measurements were defined for each measurement device and standard corrections were applied to the raw data to obtain depth-dose curves. The degree of agreement between the various techniques and the NACP-water standard was quantitatively analyzed through comparison of the resulting depths of 50% dose and practical range. All methods were found to yield reasonable results when carefully implemented, with average differences of less than 1 mm being easily achievable. Measurements with *p*-type silicon diode detectors were found to be particularly useful, as they are pointlike and appear from all practical considerations to directly represent relative dose, thus requiring little or no correction to raw readings.

I. INTRODUCTION

With the recent adoption of new dosimetry protocols,[1–4] more consistent methods of performing absolute electron dose measurements (calibrations) with different ionization chambers have been established. Those protocols require dose specification (and, where possible, measurement) in water. From consideration of the Nordic Association of Clinical Physicists (NACP) protocol,[2] a parallel-plate ionization chamber was developed specifically for electron beam measurements by Mattsson, Johansson, and Svensson.[3,5] They point out that its very narrow (2 mm) air gap and carefully designed guard ring minimize perturbation effects; its thin (<0.1 mm) collecting electrode is mounted on a thin (<0.3 mm) insulating layer yielding negligible polarity effect; and its thin (0.5 mm) graphite front wall, together with the composition and size of other structural components make it approximately water equivalent. The chamber[6] can be enclosed in a waterproof housing and attached directly to a scanning system, enabling one to perform ionization measurements in water under conditions of well-defined chamber and phantom geometry. This combination most closely approximates the spirit of the new protocols for use of an ionization chamber and requires the minimum number of corrections to raw readings.

Several methods also avail themselves for measurement of electron beam relative dose distributions.[1,7,8] This work is intended to compare practical methods used to perform routine clinical electron relative dosimetry. As such, all data were obtained in manners consistent with those one might actually use while accepting a new machine or gathering data for input to a treatment planning system. The analysis focuses on central axis depth-dose measurements obtained with small volume parallel-plate or thimble ionization chambers, solid state diode detectors, x-ray film, and thermoluminescent dosimeters (TLD). Using the NACP chamber results as a standard, the depths of 50% dose and practical range obtained with other methods are evaluated to determine what simple additional displacement or geometry corrections, if any, must be applied to obtain agreement among the data sets.

II. MATERIALS AND METHODS

Measurements were done at a source to surface distance (SSD) of 100 cm for the single and dual foil scattered electron beams generated by Varian Clinac 18 and Clinac 1800 linear accelerators, respectively.[9] Data were obtained for square field sizes of 6×6, 10×10, and 15×15 cm^2 and energies of 6, 9, 12, 15, and 18 MeV on the Clinac 18 and for field sizes of 6×6, 10×10, 15×15, 20×20, and 25×25 for energies of 6, 9, 12, 16, and 20 MeV on the Clinac 1800. Some measurements were obtained for only a subset of the energy and cone sizes available, with ease and practicality of measurement being the determining factor. Several measurements, however, were repeated at different points in time (greater than six months) to insure consistency. All dose values were determined from raw data according to the spirit of the recent, newly adopted protocols.[1–4]

The relevant dimensions of the measurement devices are

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summarized in Table I. At least 15 cm of material was always present behind each detector to insure that the electron beams were fully stopped in the phantom. For the ionization measurements, temperature and pressure were monitored and normalization runs were obtained at periodic intervals to insure the consistency of the data. Chamber bias polarity effects and ion collection efficiencies were checked for each ionization 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 data were obtained using a Therados RFA-3 phantom/positioner.[6] Its control unit has a stated resolution of 0.1 mm in position and 0.1% in normalized reading. Measurements were always performed in the same manner, with detectors moved from deeper to shallower, in order to eliminate backlash. The positioner was routinely checked for linearity and reproducibility of position by comparison to a precision steel ruler. These precautions result in better than 0.2 mm precision for reproducibly positioning the chamber. Depths in clear polystyrene (density 1.045 g/cm^3) were achieved by placing additional slabs of the 25 cm $\times$ 25 cm SCRAD-type phantom[10] in front of a detector while maintaining a constant SSD. The thickness of each slab was measured with a micrometer. Charge storage problems associated with plastic phantoms[11–13] were not found to be a problem here for our multiple slabs, as evidenced by the agreement among measurements made at the beginning and end of each running period and on different days, in agreement with the findings of Thwaites.[14]

Ionization chamber measurements were obtained with the RFA system in the water phantom using the NACP design parallel-plate chamber in its waterproof housing[5,6] and two popular 0.1 cm^3 thimble ionization chambers [PTW micro M2332 chamber in its flexible waterproof rubber sleeve, and the RK-type 83-05 thimble, also waterproof, with an outer wall of PMMA (perspex)[6]]. The effective points of measurement were taken as the center of the proximal surface of the air cavity for the NACP chamber and as 0.55 of the inner radius of the air cavity proximal to each chamber center for the thimble chambers. For each depth-ionization measurement, the chamber's effective measurement point was placed at a depth approximately 3$\times$ the estimated practical range and measurements were obtained at decreasing depths to within a few millimeters of the water surface. A second small thimble ionization chamber was placed in the corner of the radiation field and used as a monitor chamber for each set of measurements. Chambers were placed at a bias of 300 V and ionization readings were obtained through the standard RFA-3 electronics.[6] Other water measurements were obtained using a *p*-type silicon diode detector,[6] which overcomes some of the shortcomings of previous *n*-type silicon detectors supplied for such purposes.[15,16] It is encapsulated in an epoxy cylinder such that its sensitive volume is located parallel to one face of the housing, less than 0.5 mm below the surface. It was also attached to the RFA-3 positioner and data were obtained as with the NACP chamber above, with the exception that a second reference diode detector was used for monitoring the electron fluence instead of an ionization chamber.

All water phantom data were obtained under the control of a microcomputer.[17] A 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 detector current were averaged until they showed a variance of less than 0.2%. The detector was then slowly and automatically scanned until reaching (1) a location 1 cm shallower in depth, or (2) a point which received a test relative current reading value 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.

TABLE I. Central axis relative depth-dose measurement devices.

Device	Relevant dimension	Effective measurement point	Measurement medium	Corrections applied	
NACP parallel-plate chamber	0.5 mm graphite wall 0.1 mm Mylar film 2-mm air gap	Proximal surface of air cavity	Water	Air–Water stop-power ratio	
PTW 0.1 cm^3 thimble chamber	3.5-mm i.d.	1.0 mm proximal to center	Water	Air–water stop-power ratio	Fluence correction
RK 0.1 cm^3 thimble chamber	4.0-mm i. d.	1.1 mm proximal to center	Water	Air–Water stop-power ratio	Fluence correction
RFA-3 *p*-type silicon diode	0.1 mm thick 2.5-mm diameter	$<$0.5 mm below surface	Water	None	
Capintec PS-033 parallel chamber	0.0036 mm Al-poly wall; 2-mm gap	Proximal surface of air cavity	Polystyrene	Air-poly stop-power ratio	Scaling factor = 1.00
Holt–Memorial parallel chamber	4-mm poly wall 2-mm air gap	Proximal surface of air cavity	Polystyrene	Air–poly stop-power ratio	Scaling factor = 1.00
Harshaw TLD-100 LiF chips	3.2 mm$\times$3.2 mm area 0.9 mm thick	Center of chip	Polystyrene		Scaling factor = 1.00
Kodak XV-2 ready pack film	0.2-mm-thick film 0.25 mm paper front and back	Film center for perpendicular beam; depth, parallel beam	Polystyrene	Optical density to dose	Scaling factor = 1.00

All data obtained for the Clinac 1800 were measured using the automatic system. Some of the earlier measurements on the Clinac 18, however, 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. Some check measurements were also obtained under more standard conditions using the RFA-3 system as a positioner only. Each ionization chamber was manually moved to preselected points and charge was collected with a Keithley model 616 electrometer[18] for a given number of machine monitor units. Both methods of data collection led to equivalent results well within the precision of the measurements. This was expected, as the automatic system also forces the chamber to stop and stabilize before making readings of current.

The polystyrene measurements were limited to cone sizes less than 20 cm $\times$ 20 cm to maintain full scatter. Ionization chamber measurements were made on the Clinac 18 using a Holt–Memorial design parallel-plate ion chamber[10,19] and on the Clinac 1800 using a Capintec model PS-033 parallel-plate ion chamber.[20] Both chambers are imbedded in a 25 cm $\times$ 25 cm polystyrene phantom and the proximal surfaces of their air cavities were used as their effective points of measurement. The chambers were connected to a Keithley model 616 electrometer and measurements of collected charge versus depth were obtained and entered into the computer in the same standard format used for the automatically collected water data described above.

Measurements were also made in polystyrene with LiF TLD and x-ray film for 6 cm $\times$ 6 cm and 15 cm $\times$ 15 cm field sizes. The TLD chips (Harshaw TLD-100) were annealed in the standard fashion[21] and placed into machined spaces of a polystyrene sheet, such that their thinnest dimension was in the beam direction. A dose corresponding to 300 cGy at each beam's depth of nominal maximum dose was delivered to the phantom for each position of the chips. To limit the number of measurements, data were obtained in only three dose regions; three or more readings in the bremsstrahlung tail, four to five readings in the high gradient-dose falloff region, and several readings around the expected depth of maximum dose. After irradiation, the chips were post annealed and read out to obtain measurements of relative TLD reading versus depth. Raw readings were normalized by individual chip sensitivities which had been obtained previously through irradiation of the entire batch of chips to a known dose. The resulting relative dose versus depth data were also entered in the computer in the standard format for further analysis.

Films (Kodak type XV-2 ready pack film[22]) were irradiated in their packets. Each packet was slit at the corner prior to irradiation and additional sheets of polystyrene were pressed down upon the film packet in order to remove trapped air. Measurements of optical density were obtained for films irradiated perpendicular to the beam direction at different depths (one depth at a time) in the clear polystyrene phantom, for a fixed number of machine monitor units. Separate sheets of film from the same batch were irradiated perpendicular to the beam at d_{max} to known doses and processed along the test films to obtain optical density to dose conversion factors. Compared to parallel film irradiations, the perpendicular irradiations provide discrete measurements of relative optical density versus depth under conditions of greatly minimized positioning error. However, they are tedious to perform and do not provide the resolution and cost effectiveness of a single film irradiated parallel to the beam. Therefore, for interpolation, films were also irradiated nearly parallel to the beam direction for all cases investigated (at a slight angle to the beam to decrease electron streaming). The edge of each film was aligned with the surface of the polystyrene phantom. The films were scanned along the beam central axis using an automatic isodensity plotter attachment of the RFA-3 scanner. Those values were entered into the computer for further analysis together with the optical density to dose conversion factors. Values of depth of 50% dose and a practical range obtained using the parallel and perpendicular method of irradiation were compared, and the values obtained from the former were adjusted slightly in depth (if needed) to correspond with the perpendicularly irradiated readings. The continuous data obtained from the parallel irradiations were used in the discussion that follows.

III. DATA REDUCTION

Digitized data representing raw ionization readings $I'(Z)$ as a function of effective depth Z were first corrected for beam divergence[1] $\{I(Z) = I'(Z) \times [(\mathrm{VSD} + Z)/\mathrm{VSD}]^2\}$ and renormalized. Virtual point source-to-surface distances (VSD) were independently measured for each cone and energy by back projection of the 50% beam widths measured at various distances in air with a small p-type silicon diode. This method yields consistent results and a fairly constant virtual point source position, as are appropriate for the strictly geometric corrections desired here.[23,24] The divergence corrections are made to put the data in the format necessary for rigorous interpretation of the stopping-power data used below. Depths of 50% ionization were determined by fitting a straight line to the data in the approximately 60% to 30% falloff region of the divergence-corrected ionization curve. From such fits to the 15 cm $\times$ 15 cm cone measurements for the NACP chamber, the mean incident energy E_0 of each beam was obtained through multiplication of the depth of 50% ionization by the factor 2.38 MeV/cm.[25,26] Relative doses were obtained through multiplication of each ionization value by air to phantom restricted stopping-power ratios and fluence corrections (if required). All ratios and correction factors were interpolated from published tables[4] using E_0 and published chamber dimensions as input. Data were then reformatted as standard percentage depth-dose curves by reinstating the divergence dependence and renormalizing to 100%.

Reduction of the diode data proceeded along similar lines, except that no fluence or stopping-power ratio corrections were applied. The silicon to water stopping-power ratio varies quite slowly as a function of energy. Thus, its value is of little consequence for the relative measurements of interest here.[27] Also, for comparison to our NACP standard, we wish to investigate what minimal amount of corrections would be required to data obtained under practical condi-

tions in order to obtain satisfactory results for clinical use. The raw film data were corrected by the optical density to dose conversion factors mentioned above to obtain dose versus effective depth data files. Those data, along with the TLD data, were treated in much the same fashion as the diode data by assuming that they all directly represent relative dose readings. Values of relative dose versus depth were renormalized to maximum reading to form percentage depth-dose curves.

For the ionization measurements made in clear polystyrene, our interactive program computes relative dose to polystyrene as a function of physical depth in polystyrene (i.e., raw ionization values are multiplied by air-to-polystyrene stopping-power ratios). One may also obtain relative dose values as a function of effective depth in water through multiplication of the physical depths measured in polystyrene by an appropriate scaling factor. The scaling factor for our clear polystyrene phantom has been investigated thoroughly.[28] Here, we used a scaling factor of 1.00, again, to investigate what degree of agreement to the NACP results one might obtain using practical clinical measurements to obtain relative dose values.

IV. RESULTS

Fractional depth-dose curves from all sources were compared to the corresponding curves obtained with the NACP parallel-plate chamber in the water phantom for each combination of field size and energy. Representative samples of those data comparisons are presented in Figs. 1 and 2 for the measurements with detectors in water and polystyrene, respectively. The agreement is quite good, although small differences do exist. To more quantitatively define differences in the curves beyond the depth of maximum dose, linear least-squares fits of straight lines were made to 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 positioning of detectors, small changes in detector response, and electron beam fluctuations, data points immediately on either side of original 60% and 30% endpoints were identified and used as endpoints for subsequent fits. Thus, an average slope and an average intercept were computed from those fits, as were their statistical standard errors. Depths of 50% ionization and their statistical errors were computed using those average fit parameters. The depths where those lines intersected the lines fit to the bremsstrahlung tails were used as a measure of each beam's practical range.[1]

For each electron beam/cone combination, depths of divergence-corrected 50% dose and practical range measured with a particular combination of detector and phantom were compared to identical quantities measured with the NACP chamber in the water phantom. Tables of ratios of depths of 50% dose or practical range to corresponding NACP values and tables of physical differences in those quantities (mm) from NACP values were formed. The agreement among values obtained from the automatically acquired data in the water phantom was particularly good (Fig. 1) with most ratios to NACP values near 1.00 and small individual standard errors ($\sim 1\%$). Those results are attributed to initially

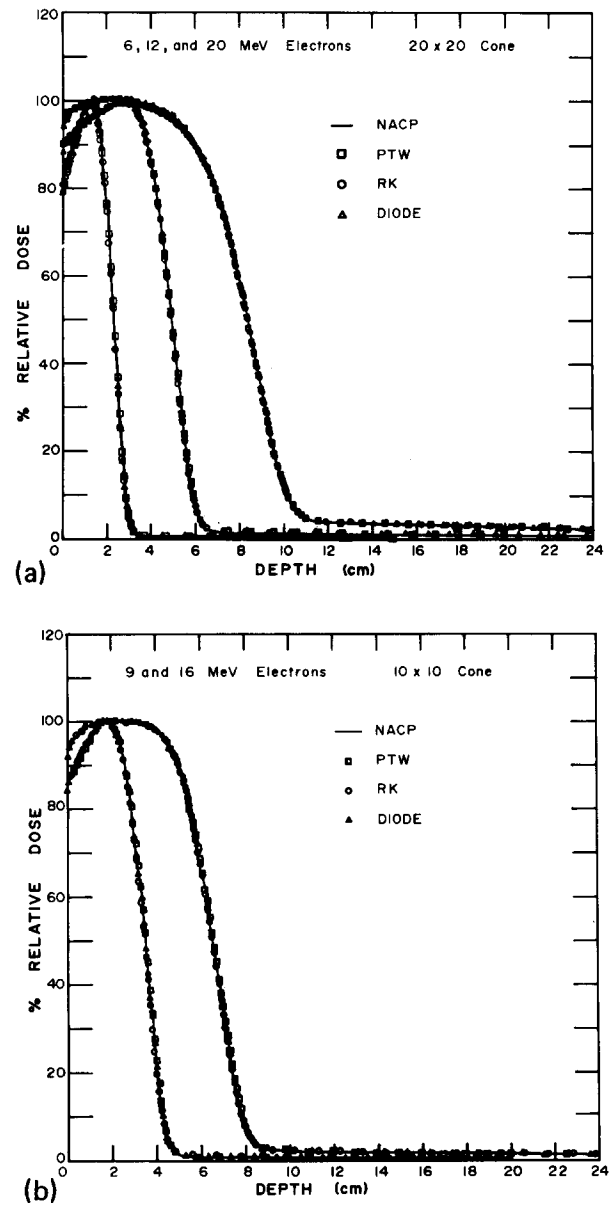

FIG. 1. Representative samples of depth-dose curves obtained with various detectors (symbols) in the water phantom to similar values obtained using the NACP chamber in the water phantom (solid line drawn through data for clarity)—100 cm SSD, Clinac 1800. (a) 20×20 cone for 6, 12, and 20 MeV; (b) 10×10 cone for 9 and 16 MeV.

positioning the chamber's effective point of measurement with great care and the reproducibility and reliability of the automated acquisition system. Somewhat larger standard errors ($\sim 2\%$) were observed in the individual Holt, Capintec, TLD, and Film ratios. They are due in part to the relatively greater statistical uncertainty in the fits to the data points in the falloff and bremsstrahlung regions, a consequence of having fewer points in each data region (Fig. 2).

More than 300 data runs were investigated. No trend in the degree of agreement among the various data sets was observed as a function of energy or field size. Therefore, weighted averages of ratios of depths of 50% dose and practical range and physical difference in the depths of those quantities were formed for each measurement device. Data were averaged over all machines, energies, and field sizes

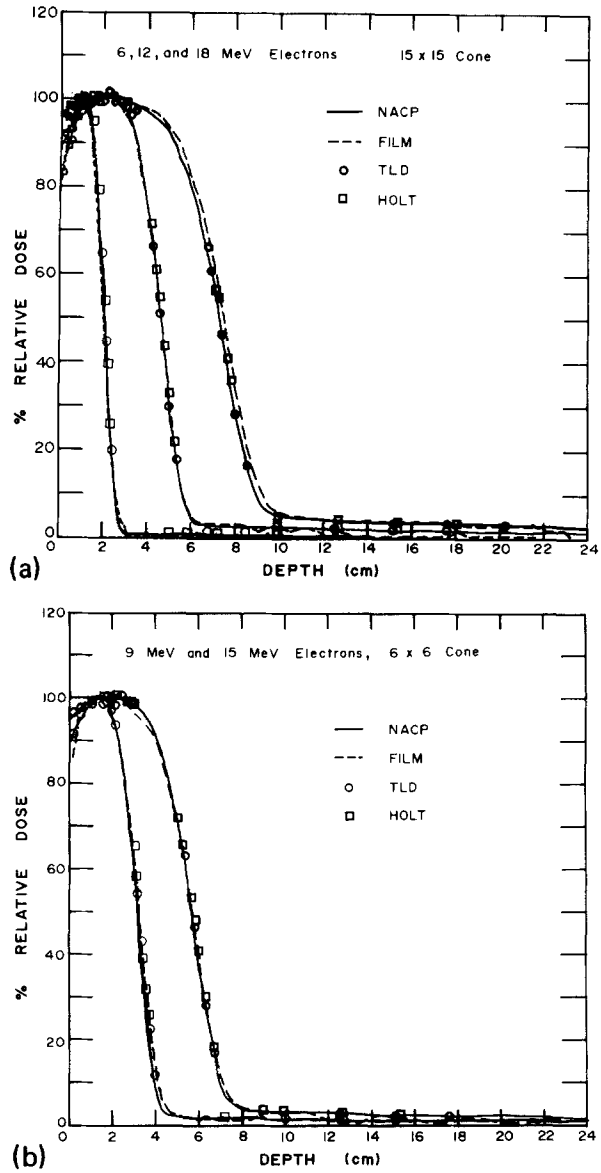

FIG. 2. Representative samples of depth-dose curves obtained with various detectors (symbols) in the polystyrene phantom to similar values obtained using the NACP chamber in the water phantom (solid line drawn through data for clarity)—100 cm SSD, Clinac 18. (a) 15×15 cone for 6, 12, and 18 MeV; (b) 6×6 cone for 9 and 15 MeV.

investigated for each detector system. In those averages, each individual ratio or difference was weighted by the inverse square of its uncertainty. The averages, together with the statistical standard errors in those mean values, are presented in Table II. We see that the overall agreement among the various data sets is quite good. The depth of 50% dose or practical range determined with any of the techniques, when averaged over energy and field size, usually agrees with our NACP chamber in water phantom standard to better than 1%. Similarly, average differences in those depths are less than 1 mm. We again note the exceptional agreement among the ionization chamber data obtained for measurements in the water phantom. The depths obtained in the polystyrene are generally larger than corresponding ones from the NACP-water combination. This is due to our use of a polystyrene to water relative depth scaling factor of 1.00. The degree of agreement could be improved for those data from our clear polystyrene phantom through use of a scaling factor nearer 0.99.[28] However, we feel that the uncorrected results suffice for routine relative clinical measurements.

The uncertainties quoted in the average values above are, as mentioned, 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 (from 10 to 55 here). 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 be constant overall displacements of unknown sign in the depths of 50% reading and practical range. Their magnitude, however, would be no larger than the statistical uncertainties quoted above.

V. DISCUSSION

We see that satisfactory agreement has been obtained among all methods described here for measurement of relative depth-dose distributions in the electron beams studied. That agreement has been accomplished using nominal points of reference and standard corrections to raw data (Table I). It has been demonstrated by comparison to a standard (NACP chamber in water) designed specifically for central axis electron beam measurements in the spirit of recent protocols. The degree of agreement holds both subjectively, by comparison of complete depth-dose curves beyond the depth of maximum dose, the objectively, through analysis of a depths of 50% dose and practical range finally obtained. It is further illustrated by the sample isodose plots shown in Fig. 3. There we compare optical density corrected isodose curves obtained with film in the clear polystyrene

TABLE II. Comparisons of depth of 50% dose and practical range found with various detectors to those measured with the NACP chamber in water. Weighted averages over all machines, field sizes, and energies (+ or − estimated uncertainty).

Method	Ratio to NACP value		Difference from NACP value (mm)	
	$d(50\%)$	Rp	$d(50\%)$	Rp
PTW-water	1.004(0.002)	1.000(0.002)	0.25(0.10)	0.05(0.10)
RK-water	1.001(0.002)	0.997(0.002)	0.10(0.10)	−0.10(0.10)
Diode-water	0.999(0.002)	1.000(0.002)	0.00(0.05)	0.05(0.05)
Holt-poly	1.019(0.006)	1.009(0.005)	0.85(0.30)	0.50(0.30)
Capintec-poly	1.007(0.004)	0.993(0.004)	0.35(0.20)	−0.40(0.25)
TLD-poly	1.007(0.005)	1.001(0.004)	0.55(0.15)	0.40(0.15)
Film-poly	1.009(0.005)	1.008(0.004)	0.45(0.15)	0.50(0.15)

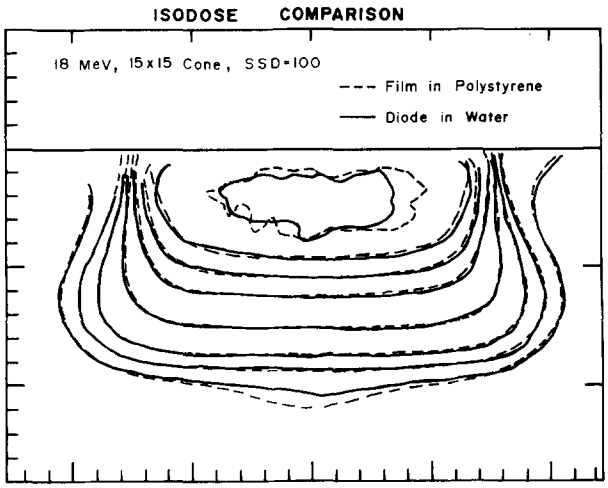

FIG. 3. Representative sample comparison of isodose curves obtained from optical density corrected film irradiated in the clear polystyrene phantom (dashed line) and from scans with the p-type silicon diode in the water phantom (solid line)—15×15 cone at 100 cm SSD for 18 MeV beam.

phantom to isodose curves measured with the p-type silicon diode detector in the water phantom. We notice a quite acceptable degree of agreement.

Initially, one of the goals of this work was to identify simple correction factors, such as shifts in effective points of measurement, to obtain sufficient agreement among the various techniques for routine clinical use. That has been achieved without iteration using the logical conditions of measurement stated in Table I. This is also a reflection of the consistency of suggested effective measurement points, stopping-power ratios, and fluence corrections stated in various protocols. It should also be noted, however, that the corrections listed (such as using a displacement correction factor for thimble chambers[1,29]) were required to achieve the results indicated above.

Overall, the ionization chamber measurements and diode measurements appear to be the most reliable, whereas the film and TLD measurements must be very carefully interpreted, especially in the buildup region. The water phantom measurements, although requiring careful setup, are simple to make and produce the most reliable results. It is deemed particularly important to use small volume chambers (especially for thimble chambers) for those relative measurements, to minimize errors in location of effective measurement points. Performing measurements with the polystyrene phantom slabs, although quite precise from consideration of physical quantities such as depth and chamber location, are quite tedious to perform. They require multiple entries into the treatment room to change depths and careful monitoring of machine conditions throughout the sometimes long course of the experiment. Some measurements performed here were done in a popular clear polystyrene phantom common to many departments in the USA and a scaling factor of 0.99–1.00 has been shown to be adequate.[28] However, as always, the composition and radiological properties of any plastic phantom should be carefully analyzed before use.

In a practical sense, we find use of the p-type silicon diodes in the water phantom to be exceptionally convenient for making most relative dosimetry measurements, such as obtaining data necessary for input to treatment planning systems and for comparisons to calculations. That is, the diodes are pointlike, they may be easily positioned in a water phantom for measurements, and, by most practical considerations, read out directly in relative dose. This all serves to eliminate sources of error and inconvenience associated with the preparation of TLDs and with conversion of ionization chamber readings and film optical densities to dose. Thus, their convenience in the automated acquisition of relative quantities such as depth-dose curves, off center ratios, and isodose plots is hard to match. This is in agreement with the conclusions of Rikner and Grusell.[27,30]

A quantitative evaluation of relative surface dose was not done here. Use of the NACP chamber in water as a standard for surface dose measurements is precluded by virtue of its finite thickness entrance window. Also, when raised to the water surface, both a meniscus is observed around the chamber housing and a variable amount of residual water clings to the chamber's front surface. Measurements with thin layers of TLD powder or extrapolation ionization chambers with thin entrance windows in a solid phantom, together with appropriate correction factors,[31] could provide appropriate standards; specialized techniques not investigated here. However, qualitative agreement among the various methods that were examined was readily and reproducibly obtained to within a few millimeters of the surface for all but the film measurements, where extreme care is required to obtain reliable results.[7,8]

Results comparable to those obtained here under similar standard conditions of measurements should be achievable in most other foil scattered electron beams. It would be useful for a similar analysis to be performed for relative measurements made in electron beams of higher energy and from machines using different modes of production, such as scanned beams.

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