How water equivalent are water-equivalent solid materials for output calibration of photon and electron beams?

V. M. Tello,[a] R. C. Tailor, and W. F. Hanson
Radiological Physics Center, Department of Radiation Physics, Box 547, University of Texas M.D. Anderson Cancer Center, 1515 Holcombe Boulevard, Houston, Texas 77030

(Received 8 July 1993; resubmitted 5 April 1995; accepted for publication 21 April 1995)

The water equivalency of five "water-equivalent" solid phantom materials was evaluated in terms of output calibration and energy characterization over a range of energies for both photon (Co-60 to 24 MV) and electron (6–20 MeV) beams. Evaluations compared absorbed doses calculated from ionization measurements using the same dosimeter in the solid phantom materials and in natural water (H_2O). Ionization measurements were taken at various calibration depths. The Radiological Physics Center's standard dosimetry system, a Farmer-type ion chamber in a water phantom, was used. Complying with the TG-21 calibration protocol, absorbed doses were calculated using eight measurement and calculational techniques for photons and five for electrons. Results of repeat measurements taken over a period of 2 1/2 years were reproducible to within a $\pm 0.3\%$ spread. Results showed that various combinations of measurement techniques and solid phantom materials caused a spread of 3%–4% in the calculation of dose relative to the dose determined from measurements in water for all beam energies on both modalities. An energy dependence of the dose ratios was observed for both photons and electrons.

Key words: water equivalent solid, phantoms, ion chamber, absorbed dose, output calibration, TG-21 calibration protocol

I. INTRODUCTION

In the past few years, several solid phantom materials have been developed as being similar enough to natural water (H_2O) that they can be used interchangeably as calibration phantoms. We evaluated the water equivalency of five "water-equivalent" solid phantom materials in terms of output calibration and energy characterization over a range of energies for both photon (Co-60 to 24 MV) and electron (6–20 MeV) beams. Our evaluation was based upon the comparison of absorbed doses calculated from ionization measurements by the same dosimeter in the solid phantom material and in water. Throughout this paper we will use the term "solid" to refer to the water-equivalent solids and the term "water" to refer to natural water.

This study was initiated when the Radiological Physics Center (RPC), which uses a water phantom during its dosimetry review visits to institutions participating in cooperative clinical trials, observed unexplained discrepancies in dose determination of up to $\pm 3\%$ between RPC calibrations and calibrations by several institutions using solid phantom materials. Several inconsistencies and points of confusion in the use of these solid phantom materials have been noted in the literature[1] and at institutions visited by the RPC. The inconsistencies and confusions which may partially account for the observed discrepancies include the following:

(a) Institutions use the "photons only" solid water™ (Radiation Measurements, Inc., Middleton, WI) to calibrate electron beams.
(b) Institutions mix slabs with different models of solid water™.
(c) Institutions use Ho and Paliwal's published values[2] of stopping powers and absorption coefficients for the wrong model solid water™; other institutions do not use Ho and Paliwal's data for the "photons only" solid water™.
(d) Confusion exists between using the d_{max} measured in water or the d_{max} measured in the solid phantom material when measuring at d_{max} in the solid phantom material.
(e) Confusion exists over whether equivalent depths are linear depths (cm) or mass depths (g/cm^2).

In a strict dosimetric sense, water equivalency requires that the dosimeter signals measured with the same dosimeter in both the solid and water are the same. This must apply to all photon and electron beams, at all depths of use and at all energies. This paper consolidates results on various solid phantom materials presented as posters over the past few years.[3–5]

The RPC's main concern in the evaluation of solid phantom materials lies with any potential impact on dose delivery when these solid phantom materials are used in the place of water for beam energy characterization and absolute dose calibrations using the AAPM calibration protocol.[6] This paper presents results on the dosimetric evaluation of these solid phantom materials. The calculated doses in water from ionization measurements in the solids under various calibration conditions are compared with the dose calculated from measurements in water at d_{max} using the same dosimeter. Our definitions are internally consistent so that the dose calculated from measurements in water at the recommended 5 or 7 cm depth for photons is identical to that from measurements at d_{max}. A great deal of time and effort has been devoted to minimize the uncertainties introduced by the physical parameters involved in the measurement and calculation of absorbed dose in water and in the solid phantom materials.

 0094-2405/95/22(7)/1177/13/$6.00

TABLE I. Machines, beams, and energies used in evaluation of water-equivalent solid phantom materials.

Unit (Location)	Beam	IR[a]	E_0 (MeV)[b]
Eldorado (M. D. Anderson)	Co-60	0.572	
VARIAN			
Clinac 6/00 (Univ. of New Mexico)	6 MV x rays	0.674	
Clinac 2100 C (M. D. Anderson)	6 MV x rays	0.673	
	18 MV x rays	0.786	
	6 MeV e^-		5.6
	9 MeV e^-		8.4
	12 MeV e^-		11.0
	16 MeV e^-		15.1
	20 MeV e^-		19.1
Clinac 2500 (Univ. of New Mexico)	24 MV x rays	0.800	
Clinac 2100 C (Mayo)	10 MV x rays	0.737	
SIEMENS			
Mevatron KD (M. D. Anderson)	6 MV x rays	0.679	
	18 MV x rays	0.783	
	6 MeV e^-		4.5, 4.7, 4.9[c]
	12 MeV e^-		10.4
	15 MeV e^-		12.4, 12.9[c]
	20 MeV e^-		18.5
Mevatron 74 (Baylor)	10 MV x rays	0.741	
Mevatron 77 (Baylor)	15 MV x rays	0.762	
Mevatron KD (Methodist)	6 MV x rays	0.673	
	23 MV x rays	0.789	

[a]Ionization ratio (IR) for photon beams, per the AAPM protocol (see Ref. 6).
[b]Mean incident energy ($\bar{E}_0$) for electron beams.
[c]Represents minor fluctuations in beam energy over two years.

A discussion of uncertainties verifying a maximum spread of 0.3% in our results is provided in Sec. IV.

II. MATERIALS AND METHODS

The same dosimetry system was used for all beam measurements in water and in the various solid phantom materials. It consisted of a PTW N23333, 0.6 cm^3 Farmer-type cylindrical chamber with an acrylic wall, (PTW-Freiburg, Germany) a Keithley 602 electrometer (Keithley Instruments, Inc., Cleveland, Ohio), and a Data Precision 255 digital multimeter (Data Precision, Danvers, MA). The 0.46-cm acrylic protective cap was used on the chamber when the measurements in water were taken. The solid phantom materials were machined to accept the chamber with no build-up cap.[7] A series of similar measurements were made with an NEL model 2571 Farmer 0.6-cm^3 chamber with a graphite wall (Nuclear Enterprises, LTD. Beenham, Reading, England), a Keithley 602 electrometer, and a digital multimeter. This was done to establish the independence of the results with a change in thimble-wall material.

A Co-60 unit and a number of linear accelerators (linacs) at The University of Texas M. D. Anderson Cancer Center and various other institutions, as listed in Table I, were used for the work presented in this paper. The trade names and physical characteristics of the five solid phantom materials evaluated in this work are summarized in Table II.

All solid phantom materials consisted of 20-cm-square or 30-cm-square slabs of various thicknesses, ranging from 1 mm to 5 cm. Each solid phantom material had one slab with

TABLE II. Physical characteristics of five water-equivalent solid phantom materials.

Trade name and use	Color	Slab area (cm^2)	Density	
			Mean	Spread[a]
Solid water SW-451 for photons only	Ochre brown	20×20	1.024	1.2%
Solid water SW-457a[b] for electrons only	Ochre brown	30×30	1.019	2.4%
Solid water SW-457 for photons and electrons	Reddish brown	20×20	1.045	4.0%
White water RW-3 for photons and electrons	White	30×30	1.045	2.0%
Plastic water, PW,[c] for photons and electrons	Lavender	30×30	1.014	1.1%

[a]This represents maximum to minimum variation.
[b]It is unclear whether this type of solid was ever commercially available. It has the same model number as the new photon and electron solid. They can be distinguished by their density and slight color difference.
[c]Chemical composition of this resin in terms of fractional weight is (C) 0.6282, (O) 0.1794, (H) 0.0925, (N) 0.0100, (Ca) 0.0795, (Cl) 0.0096, and (Br) 0.0003 as provided by Computerized Imaging Reference Systems, Inc., Norfolk, VA (see Ref. 8).

a cavity to accept a 0.6-cm^3 Farmer-type ion chamber without the build-up cap.

Three of the solid phantom materials were manufactured by Radiation Measurement, Inc. (RMI) Middleton, WI. Our institution obtained a solid water™ phantom sometime around the mid 1980's; this phantom was intended for use specifically for electron dosimetry. We understood that the phantom was a prototype for a new formula specific for electrons; however, it is stamped with the model No. 457. We will label this material SW457a to distinguish it from the SW457 material purchased by the authors in early 1990. It is not clear to us whether this formula (SW457a) was ever commercially available. Plastic water™ was developed by Computerized Imaging Reference Systems Inc. Norfolk, VA, and is also marketed by Nuclear Associates, Inc. Carle Place, NY. Model RW3 white water is manufactured by PTW-Freiburg, Freiburg, Germany and marketed by Nuclear Associates, Inc. This is a high-impact polystyrene containing TiO_2. Some physical characteristics for solid water™ are published elsewhere.[2,8] Although not stated in these papers, we understand this is the RMI model 451 solid water.

The thickness of the slabs was measured with a micrometer. The maximum difference in thickness measured anywhere on a slab of solid phantom material was found to be 0.2 mm. The slab masses were determined to an accuracy of 0.1 gram. The spread in densities shown in Table II for slabs of the same solid phantom materials are, therefore, outside our measurement uncertainty.

All measurements were made along the central axis of a 10 cm×10 cm field size for a constant target-to-surface distance of 100 cm for all beams (80 cm for the Co-60 beam). Quality assurance tests were implemented to minimize effects of machine output drift:

(a) An external monitor (0.6-cm^3 Farmer-type ion chamber, mounted in the collimator system) was used for all linac measurements. This monitor chamber was placed so that the ^{60}Co build-up cap with the tip of the ion chamber were just inside the light field. This assured reproducible response with minimal perturbation of the photon and electron beams.

(b) As a redundant verification of output drift, the output was monitored at the start and completion of each run and periodically during each run. The dosimetry system used was a Farmer-type 0.6-cm^3 chamber in a fixed geometry in a SW457 solid water™ phantom.

The in-water ionization measurements were made in a 30 cm×30 cm×45 cm custom-designed water phantom. Meniscus (surface tension) effects in depth measurements were eliminated by the use of a custom-designed water-depth ruler so that the positioning accuracy of the ion chamber in the water phantom was within 0.3 mm. In order to maintain the constancy of nominal source-to-surface distance (SSD) and chamber depth, water level was closely monitored for water evaporation. The depths of maximum ionization (d_{max}) for both photon and electron beams were searched in 1–2 mm increments.

In solid phantom materials, the linear depth of the chamber's axis was determined to within 0.3 mm. The d_{max} searched in 1–2 mm increments, was determined by interpolation of the plotted depth-ionization data. The slabs were shuffled to maintain a fixed SSD. In this method one or more slabs are moved from underneath the probe to a position above the probe or vice versa. Thus the total number of slabs in the solid phantom stack remains constant and the SSD also remains constant. The couch supporting the stack of slabs was not moved during these measurements. As a redundancy check, the SSD was also periodically checked with the mechanical distance indicator. To provide an adequate backscatter, at least 10 cm of the solid phantom material was under the point of measurement at all times.

The effective point of ionization measurement was assumed to be the center of the thimble for photons and to be 2 mm shallower for electrons (TG-21,[6] TG-25[9]). The temperatures of the water and the solid phantom materials were periodically determined with a mercury thermometer and a thermocouple probe (model 450-AKT, OMEGA Engineering, Inc., Stamford, CT), respectively, each device having a 0.1 °C precision. Comparison of the two devices in water showed an agreement within 0.3 °C. The water temperature, initially set to 1 °C less than the room temperature, showed a minimal drift. The solid phantom materials were left in the treatment room for several hours to attain temperatures very close to room temperature. Periodic measurements showed temperatures of all solid phantom materials and the water phantom to be always within 1 °C of the room temperature. The ion chamber was allowed to equilibrate[10] with the phantom temperature for at least 5 min. before measurements were taken. Atmospheric pressure was measured with an aneroid barometer (Taylor Environmental Instruments, Fletcher, NC) that had been matched to within 0.5 mm Hg with mercury barometric pressure (corrected for temperature and latitude). Ion collection efficiency correction (P_{ion}) was determined by the two-voltage technique described first by Boag[11] and then by Boag and Currant.[12] The maximum differences in P_{ion} for measurements in the different media were less than the statistical spread in ionization readings. As such, P_{ion} was assumed independent of the measurement medium and thus not used in our calculated output ratios.

III. CALIBRATION METHODS AND CALCULATIVE TECHNIQUES

The absorbed dose to water was calculated from ionization measurements in water and in solid phantom material using the TG-21 calibration protocol Eq. (9). Absorbed dose to water at d_{max} is considered to be the standard and the reference dose. For electrons, this dose was determined from measurements at d_{max} in water. For photons, this dose was calculated from measurements at 5 or 7 cm depth in water. Depth dose in water was determined from measurements with the same chamber at 5 or 7 cm and at d_{max}. A unity replacement factor (P_{repl}) is used at d_{max} and a nonunity value elsewhere so that our absorbed dose at d_{max} is identical whether measured at d_{max} or at 5 or 7 cm depth in water. The depth of 5 cm was used for photon beam energies less than 15 MV and 7 cm was used for higher photon beam energies.

Data will be presented as the ratio of the dose at maximum d_{max} determined from ionization measurements in the

TABLE III. Description of calculative techniques for output calibration from ionization measurements in solid phantom materials.

PHOTONS:

Technique	Depth of measurement	Depth dose data used
I	cm of solid equal to water d_{max} (cm)[a]	N/A
II	g/cm^2 of solid equal to water d_{max} (g/cm^2)	N/A
III	Solid d_{max}	N/A
IV	5 or 7 cm of solid	fdd measured in water
V	5 or 7 cm of solid	fdi measured in water
VI	5 or 7 g/cm^2 of solid[b]	fdd measured in water
VII	5 or 7 g/cm^2 of solid[b]	fdi measured in solid
VIII	5 or 7 cm of solid	fdd measured in solid

[a]The depth in solid measured in cm is equal to the depth (in cm) where d_{max} occurred in water.
fdd=fractional depth dose at 5 or 7 cm depth.
fdi=fractional depth ionization at 5 or 7 cm depth.
[b]Measurements at 5 or 7 g/cm^2 in solid used depth dose or depth ionization measurements at 5 or 7 cm depth in water.

ELECTRONS:

Technique	Depth of measurement	Depth for determining L/ρ & P_{repl}
I	cm of solid equal to water d_{max} (cm)	water d_{max} (cm)
II	g/cm^2 of solid equal to water d_{max} (g/cm^2)	water d_{max} (cm)
III	Solid d_{max}	water d_{max} (cm)
IV	Solid d_{max}	Solid d_{max} (cm)
V	Solid d_{max}	Solid d_{max} (g/cm^2)

solid phantom material divided by the dose at maximum determined from ionization measurements in water. This is referred to as the ratio solid/water. d_{max} in the solid phantom materials was determined from measurements using the various depths of measurements and depth dose data indicated in Table III. For photons, the fractional depth ionization (fdi), is the ratio of ionization at depth (I_d), to ionization at the depth of maximum ionization (I_{max}).

$$\text{fdi}=\frac{I_d}{I_{max}}.$$

The fractional depth dose (fdd), includes P_{repl}, which is unity at the position of maximum ionization and non unity at any other depth d.

$$\text{fdd}=\frac{I_d\times P_{repl}}{I_{max}\times 1.000}.$$

We used the following deviations and extensions of the RPC measurements and calculative procedures outlined in TG-21:

(a) For electron beams, the half-radius shift (TG-25) to the effective point of measurement was used for all depths, including d_{max}.
(b) A 0.46-cm acrylic protective cap was used for all measurements in water. For photon-dose calculations, the acrylic cap was considered to be part of the acrylic wall of the PTW chamber. A cap correction factor[7] to account for the presence of the protective cap was applied for electrons and for photons when measurements were made with a graphite-thimble chamber.
(c) For all solid phantom materials, stopping power and absorption coefficient data for water were used. Since such data were available[2] for the "photons only" model 451 solid water™, results using these data were also calculated (see results inside parentheses in Table IV and in Figs. 5–7 as Ho corrected).

The following inconsistencies in the use of these solid phantom materials have been observed:

(a) Equivalent depth was assumed to be physical depth or equivalent mass depth (density scaled). Depth scaling between materials is not a simple matter; however, the most frequent scaling method is scaling by physical density.
(b) D_{max} is depth of maximum ionization in water or in solid phantom material.
(c) Photon calibrations were performed at d_{max} or at depth (5 or 7 cm or 5 or 7 g/cm^2).
(d) Depth ionization for photons was frequently used for depth dose. However, fractional depth dose (fdd) is related to fractional depth ionization (fdi): fdd=fdi$\times P_{repl}(d)$, at depth d.

We have, therefore, identified the measurement/calculative techniques, summarized in Table III, that may be used to determine photon or electron beam output. Note that some of these techniques may be contrary to manufacturers or protocol recommendations; however, they represent techniques noticed by the RPC.

IV. UNCERTAINTIES

It was our aim to attain a measurement uncertainty of ±0.2% in the final results. To attain this, attention was paid to every possible source of uncertainty. For every depth setting, the SSD was verified to better than 0.5 mm using a

TABLE IV. The dose ratio, solid/water, for all comparisons made for both photons and electrons. Results using Ho and Paliwal [Med. Phys. **13**, 403 (1986)] L/ρ, μ/ρ values for the solid phantom material SW-451 (photons only).

			Techniques							
Beam	IR/E_0	Unit	I	II	III	IV	V	VI	VII	VIII
Solid phantom material: PW										
Co-60	0.572	Eldorado	1.002	1.002	1.002	1.010	1.001	1.014	1.005	1.010
6×	0.673	Cl 2100	0.997	0.997	0.997	1.012	1.005	1.015	1.007	1.005
	0.674	Cl 6/100	0.994	0.994	0.994	1.004	0.996	1.006	0.998	1.002
	0.679	KD	0.997	0.997	0.997	1.011	1.003	1.013	1.005	1.004
10×	0.741	MeV 74	0.999	0.999	0.999	1.012	1.005	1.014	1.008	1.006
15×	0.762	MeV 77	---	---	---	1.013	1.007	1.015	1.008	---
18×	0.783	KD	1.000	1.000	1.000	1.006	1.001	1.010	1.004	1.006
	0.786	Cl 2100	0.999	0.999	0.999	1.007	1.001	1.011	1.005	1.005
24×	0.800	Cl 2500	0.996	0.996	0.996	1.005	0.999	1.008	1.002	1.002
6*e*	4.9	KD	0.996	0.996	0.996	0.996	0.996			
	5.6	Cl 2100	1.000	1.000	1.000	1.000	1.000			
9*e*	8.4	Cl 2100	0.997	0.997	0.997	0.997	0.997			
12*e*	10.4	KD	0.998	0.998	0.998	0.998	0.998			
	11.0	Cl 2100	1.002	1.002	1.002	1.002	1.002			
16*e*	15.1	Cl 2100	1.004	1.004	1.004	1.004	1.004			
20*e*	18.5	KD	0.999	0.999	0.999	0.999	0.999			
	19.1	Cl 2100	1.002	1.002	1.002	1.002	1.002			
Solid phantom material: RW-3										
Co-60	0.572	Eldorado	---	---	---	1.004	0.995	1.017	1.008	---
6×	0.674	Cl 2100	0.998	0.999	0.999	1.005	0.997	1.016	1.008	1.007
10×	0.741	MeV 74	0.990	---	---	0.996	0.990	1.005	0.999	---
15×	0.762	MeV 77	---	---	---	0.996	0.990	1.003	0.997	---
18×	0.784	Cl 2100	0.984	0.983	0.986	0.989	0.983	1.002	0.997	0.991
6*e*	5.5	Cl 2100	0.978	0.978	0.978	0.978	0.979			
16*e*	14.6	Cl 2100	0.994	0.993	0.994	0.994	0.995			
Solid phantom material: SW-451 for photons only										
6×	0.682	KD	0.999	0.999	0.999	1.003	0.995	1.009	1.001	1.007
			(1.008)	(1.008)	(1.008)	(1.012)	(1.005)	(1.018)	(1.010)	(1.016)
18×	0.777	KD	0.989	0.989	0.989	0.995	0.989	1.001	0.995	0.996
			(1.010)	(1.010)	(1.010)	(1.015)	(1.009)	(1.022)	(1.016)	(1.017)
	0.783	MeV 80	0.975	0.975	0.975	0.985	0.979	0.991	0.985	0.980
			(0.995)	(0.995)	(0.995)	(1.005)	(0.999)	(1.011)	(1.005)	(1.000)
6*e*	4.5	KD	0.984	0.983	0.985	0.987	0.992			
15*e*	12.4	KD	0.986	0.985	0.986	0.988	0.989			
Solid phantom material: SW-457a										
6×	0.682	KD	0.995	0.995	0.996	1.003	0.995	1.007	0.999	1.004
18×	0.776	KD	0.986	0.987	0.987	0.987	0.991	1.002	0.996	0.993
	0.783	MeV 80	0.980	0.979	0.982	0.997	0.991	1.002	0.996	0.988
6*e*	4.5	KD	0.977	0.975	0.984	0.989	0.993			
15*e*	12.4	KD	0.987	0.986	0.987	0.990	0.991			
Solid phantom material: SW-457										
Co-60	0.572	Eldorado	---	---	---	1.009	1.001	1.024	1.015	---
6×	0.662	Cl 6/100	0.991	---	---	1.001	0.993	1.010	1.002	---
	0.673	KD 23	---	---	---	1.000	0.992	1.009	1.001	---
	0.674	Cl 6/100	0.994	0.994	---	1.002	0.994	1.012	1.004	---
	0.674	Cl 2100	0.997	0.998	0.999	1.008	1.001	1.019	1.011	1.007
	0.682	KD	0.992	0.991	0.992	1.005	0.997	1.015	1.007	1.000
10×	0.737	Cl 2100	---	---	---	1.002	0.995	1.011	1.004	---
	0.741	MeV 74	0.992	---	---	1.003	0.997	1.012	1.006	---
15×	0.762	MeV 77	---	---	---	1.002	0.996	1.009	1.003	---
18×	0.776	KD	0.986	0.988	0.989	0.993	0.987	1.005	0.999	0.995
	0.783	MeV 80	0.984	0.984	0.984	0.992	0.986	1.004	0.999	0.989
	0.784	Cl 2100	0.990	0.987	0.990	0.996	0.991	1.008	1.002	0.996
23×	0.789	KD 23	---	---	---	0.989	0.983	1.000	0.994	---
24×	0.800	Cl 2500	0.986	0.984	---	0.989	0.984	1.000	0.994	---
6*e*	4.7	KD	0.978	0.977	0.985	0.988	0.992			
	5.2	Cl 2100	0.986	---	---	---	---			
	5.5	Cl 2100	0.985	0.985	0.985	0.986	0.987			
9*e*	7.9	Cl 2100	0.990	---	---	---	---			
12*e*	10.8	Cl 2100	0.990	---	---	---	---			
15*e*	12.9	KD	0.985	0.986	0.987	0.990	0.992			

Table IV. (*Continued.*)

Beam	IR/E_0	Unit	Techniques							
			I	II	III	IV	V	VI	VII	VIII
16*e*	14.6	Cl 2100	0.993	0.993	0.993	0.993	0.994			
	15.2	Cl 2100	0.993	0.993	0.993	---	---			
20*e*	18.4	Cl 2100	0.996	0.996	0.996	---	---			

mechanical pointer. Water evaporation was carefully monitored to maintain constant SSD and depth throughout the in-water measurements. Meniscus effects on depth measurements in water were minimized by the use of a device we designed so that ion-chamber water depth position was set to better than ±0.3 mm. The thickness of solid phantom material slabs varied by 0.2 mm. The depth of the axis of the chamber in solid phantom material slabs was determined to within 0.3 mm. The density of solid phantom materials was measured to within ±1% and temperature was measured to within ±0.1 °C. The reproducibility of ionization readings on a given day was 0.15%, and thus constituted the major contributor to the predicted overall uncertainty. The effect of any output drift was accounted for by monitoring the output at frequent intervals, with a 0.6-cm^3 cc Farmer-type ion chamber in a solid phantom at a fixed depth, in a fixed geometry. Compounding these uncertainties in quadratures predicted a ±0.3% overall uncertainty in the final results (one standard deviation). Figure 1 shows data verifying that these estimates may in fact overestimate this overall uncertainty. We have repeated measurements on 36 combinations of measurement techniques and phantom materials. These repeats include photon and electron beams measured two or three times. Some of these repeated measurements were separated by up to two years. The mean of the measurements for a given combination of measurement technique and phantom material was obtained, and a frequency histogram of the deviation of the individual measurement from the mean is presented. One standard deviation is less than 0.2% with no single measurement exhibiting a deviation from the mean exceeding 0.3%. In an effort to verify that these results are chamber independent, a series of measurements were made with two different Farmer-type chambers; a PTW N23333 chamber with an Acrylic thimble and an NEL 2571 chamber with a graphite thimble, the results are shown in Table V, they verify the agreement within the ±0.3% measurement uncertainty.

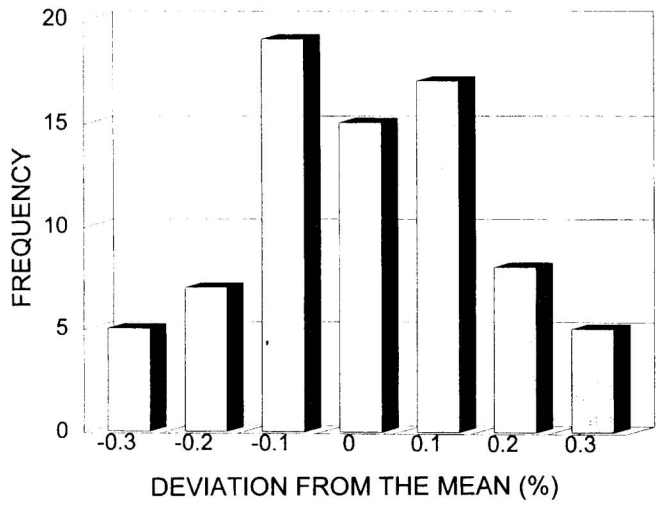

FIG. 1. A frequency histogram showing the reproducibility of our measurements. The abscissa is the deviation of each individual value from the mean, for all phantom and technique combinations for which repeat measurements were made.

V. RESULTS

The dose at the depth of maximum dose (D_{max}) calculated from the various techniques described above were divided by D_{max} calculated from measurements in water. This ratio is identified as the solid/water ratio. Table IV shows the results for all solid phantom materials, all beams (photons and electrons), and all techniques. The techniques (I–VIII) refer to those listed in Table III. The photon results listed for SW451 were determined using stopping powers and absorption coefficients for water. The values for SW451, which are shown inside parentheses, were determined using stopping powers and absorption coefficients from Ho and Paliwal.[2]

There are some important observations that emerge from this work. We begin by examining results of the most frequently used techniques for beam-output calibration (tech. I and V for photons; tech I for electrons). Data are presented as the dose ratio, solid/water, as a function of the beam energy. The beam energy is expressed as the mean incident electron energy, $\bar{E}_0$, for electrons and the ratio of the TMR at 20 and 10 cm depths, $\mathrm{TMR}|_{10}^{20}$, for photon beams from the AAPM protocol.[6] Figure 2 shows results for electrons, from measurements in various solid phantom materials (tech. I) at the depth of maximum ionization I_{max} in water. The PW data are within 0.5% of that of water, with the suggestion of a trend toward lower values at low energies. All other solid phantom materials show measurable energy dependence averaging 1% low at the high energies and 2% low at the low energies.

Although most institutions do not search d_{max} in solid phantom materials, we might expect that to yield better results. Data for this technique (technique IV) are presented in Fig. 3. The values for solid water™ model SW457 and SW457a at 5 and 13 MeV are improved slightly. A further improvement in the results might be expected if the stopping-power (L/ρ) values used were based on the mass depth (g/cm^2) rather than the physical depth (cm). This is our technique V, and the data for this are shown in Fig. 4. The

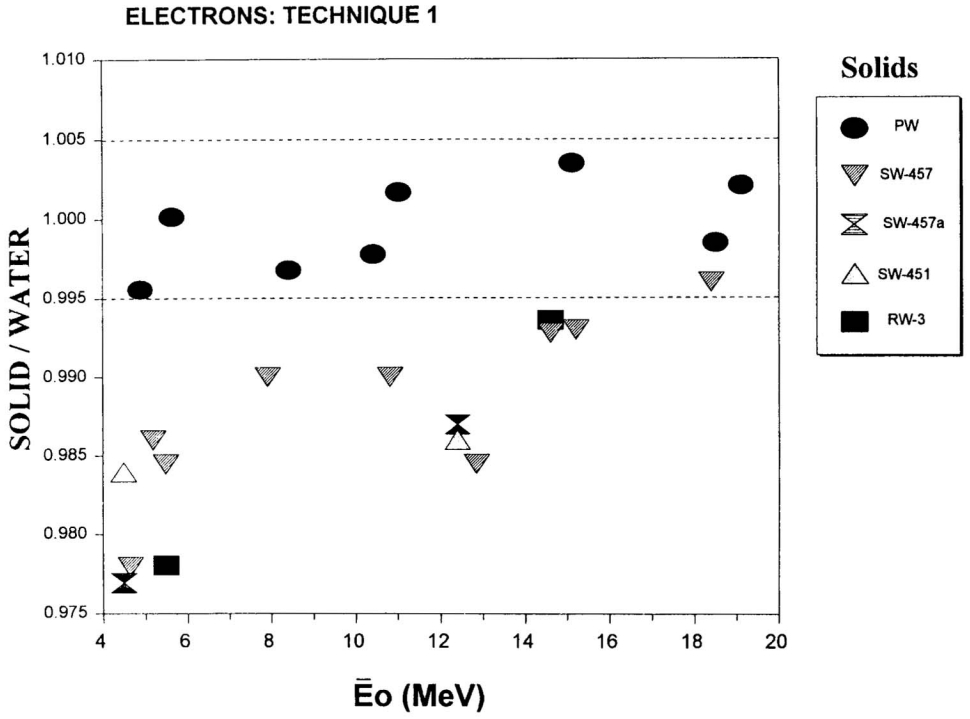

FIG. 2. The dose ratio, solid/water, as a function of $(\bar{E}_0)$ using technique I. The measurements in the solid were made at the depth of I_{max} in water and this depth (cm) was used to determine the L/ρ and P_{repl} values.

values for PW do not change, as the density of the solid phantom material is very near unity. However, the values for all other solid phantom materials do tend toward unity.

Our dose ratio, solid/water for electrons using our technique III is equivalent to the fluence ratio measurements by Thwaites.[13] Thwaites' values for the solid water™ phantom material that we believe is SW451 for nominal energies 5, 7.5, and 10 MeV are consistently 0.3% higher than our values for similar energies. This minor difference is well within the stated uncertainties. In fact, our results are basically the same as those of Thwaites for all three solid water™ materials SW451, SW457, and SW457a. Thwaites also presents results for clear and white polystyrene. Whether his white polystyrene is the same material as our RW3 is unclear.

For photons, data for technique I (ionization measurements in solid phantom materials at the depth of maximum ionization I_{max} in water) are presented in Fig. 5. The PW data are within 0.6% those of water. All other solid phantom materials cluster in a band 1%–1.5% wide with an average value near 0.99 for 6 MV x rays (TMR $|_{10}^{20}\cong 0.67$), and 0.98_5 for 18 MV x rays (TMR$|_{10}^{20}\cong 0.80$). Data for SW451 using the Ho and Paliwal[2] values for L/ρ and μ/ρ are included and represent an improvement for higher energies. Calculations from measurements at I_{max} in the solid phantom material (technique III) show no significant improvement over technique I and are not presented here.

Following the recommendation of the AAPM protocol,[6] physicists frequently obtain beam-output calibration by performing ionization measurements at depth (5 or 7 cm). Figure 6 shows results for this technique (technique V), a direct comparison of dose from ionization measurements in the solid phantom material versus those at the same physical depth (cm) in water. The trend with energy seen in technique I is also seen here; however, there is a slight shift to better agreement with water at the higher energies.

Figure 7 shows the results for technique VII in which the measurements are made at the equivalent mass depth (5 or 7 g/cm^2 in solid and 5 or 7 cm depth in water). All ratios are shifted to higher values averaging 1.01 at Co-60, nearly 1.00_5 at 6 MV, and 1.00_0 at 18 MV x rays.

For PW solid phantom material, the best results are obtained for measurements at d_{max} over all photon energies. For all other solid phantom materials, the best results obtained at low photon energies are for technique V, while at

TABLE V. Reproducibility of results with different Farmer-type ion chambers of different wall materials.

Technique	8 MV x rays IR=0.783, MeV-80 PTW/NEL[b]	7 MeV electrons E_0=6.2 MeV, MeV-80 PTW/NEL
I	1.000 (0.998[c])	0.999
II	1.000	0.999
III	1.000	0.999
IV	0.999	---
V	0.999	---
VI	1.004	N/A
VII	1.004	N/A
VIII	1.000	N/A

[a]PTW: 0.6 cc PTW N23333.
[b]NEL: 0.6 cc NEL 2571.
[c]Siemens KD (IR=0.777).

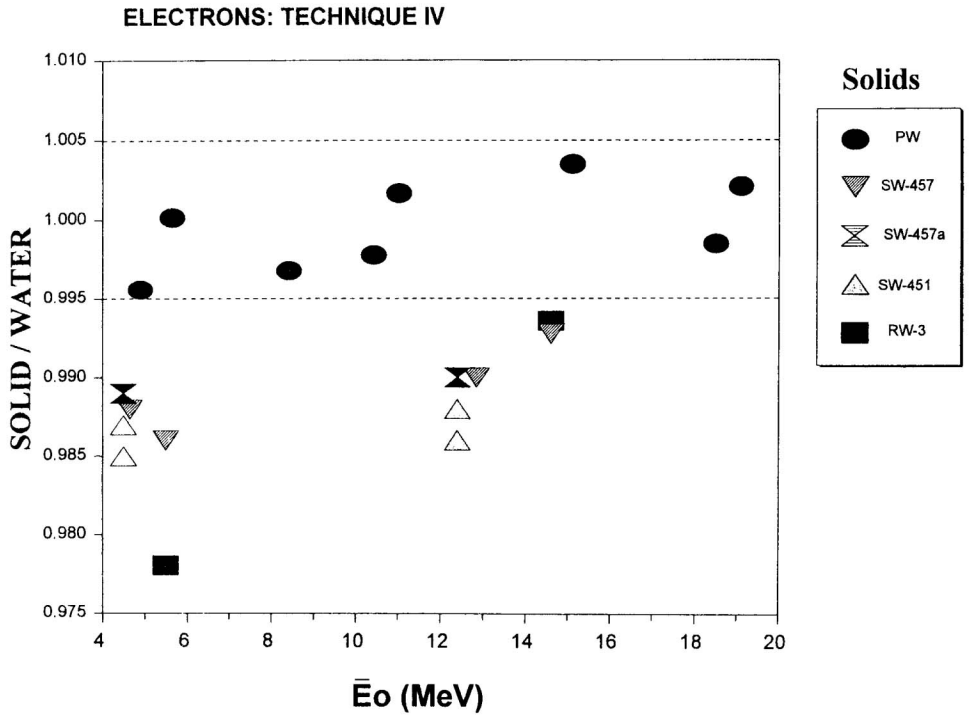

FIG. 3. The dose ratio, solid/water, as a function of $(\bar{E}_0)$ using technique IV. The measurements in the solid were made at the depth of I_{max} in the solid and this depth (in cm) was used to determine L/ρ and P_{repl} values.

higher photon energies, technique VII appears better.

The RPC is concerned with consistency of dosimetry from institution to institution. Comparison of results for all combinations of measurement techniques, solid phantom material and beam reveals the level of increased inconsistency. Figures 8 and 9 show the solid/water ratios for both photons and electrons, respectively. Two important observations emerge from these figures. First, the combination of

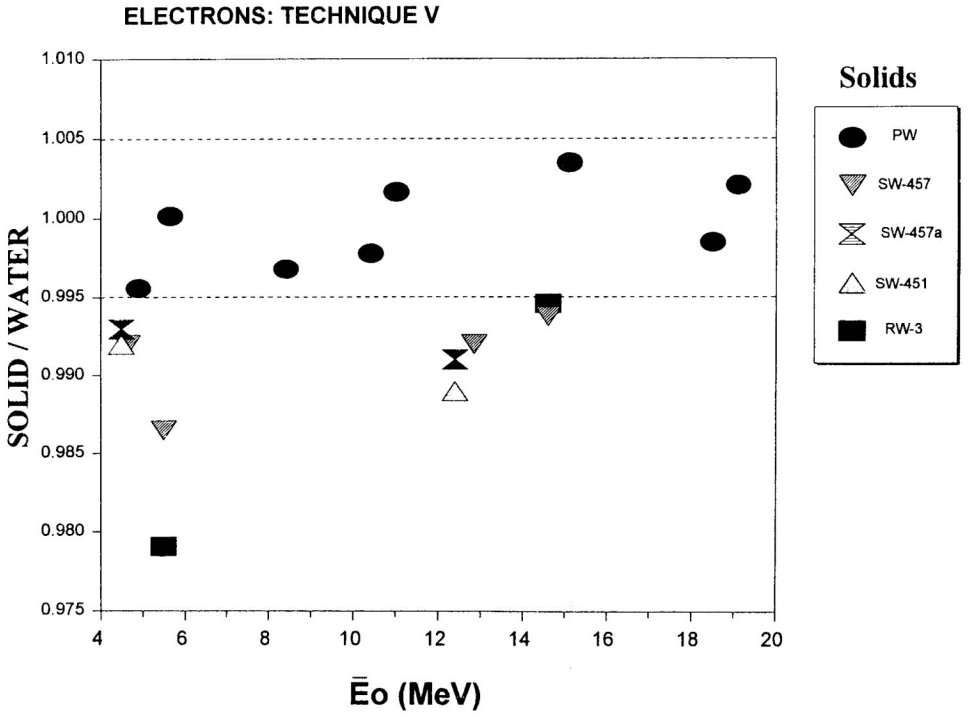

FIG. 4. The dose ratios, solid/water as a function of $(\bar{E}_0)$ using technique V. The measurements in the solid were made at the depth of I_{max} in solid and this depth (in g/cm^2) was used to determine L/ρ and P_{repl} values.

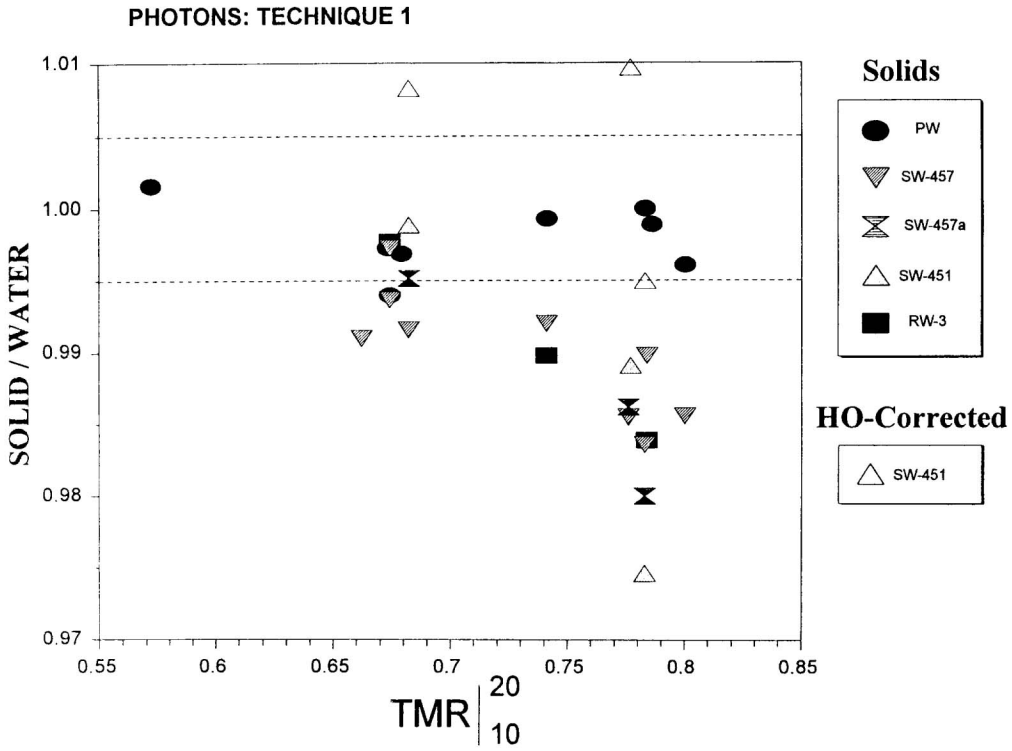

FIG. 5. The dose ratio, solid/water, as a function of $TMR|_{10}^{20}$ using technique I. The measurements in solid were made at the depth (cm) of I_{max} in water.

techniques/solid phantom materials causes a significant spread in results at all energies. The spread in data points ranges from 3.5% to 5% for photons and 2.5% for electrons. The main reason for the lesser spread for electrons may be that measurements were made only at d_{max}. Second, the results show an energy dependence, the solid phantom material-to-water ratio decreasing for higher-energy photons and lower-energy electrons. It is to be noted that the spread

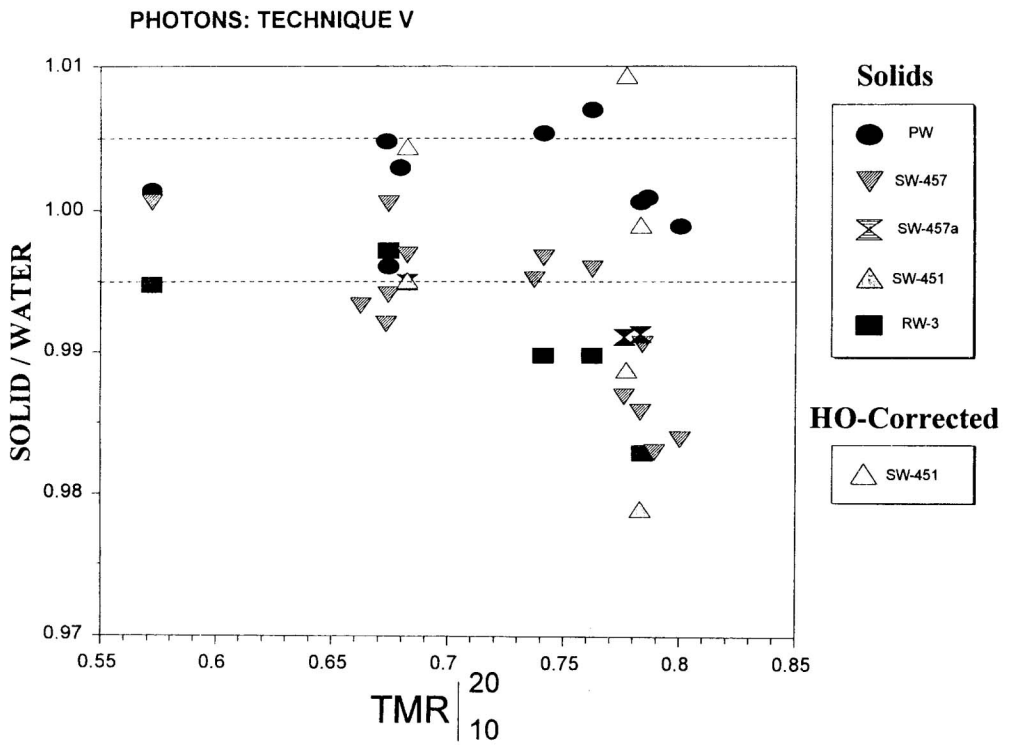

FIG. 6. The dose ratio, solid/water, as a function of $TMR|_{10}^{20}$ using technique V. The measurements in solid were made at 5 or 7 cm depth and the fractional depth ionization at 5 or 7 cm depth and the fractional depth ionization at 5 or 7 cm depth measured in water was used to determine D_{max}.

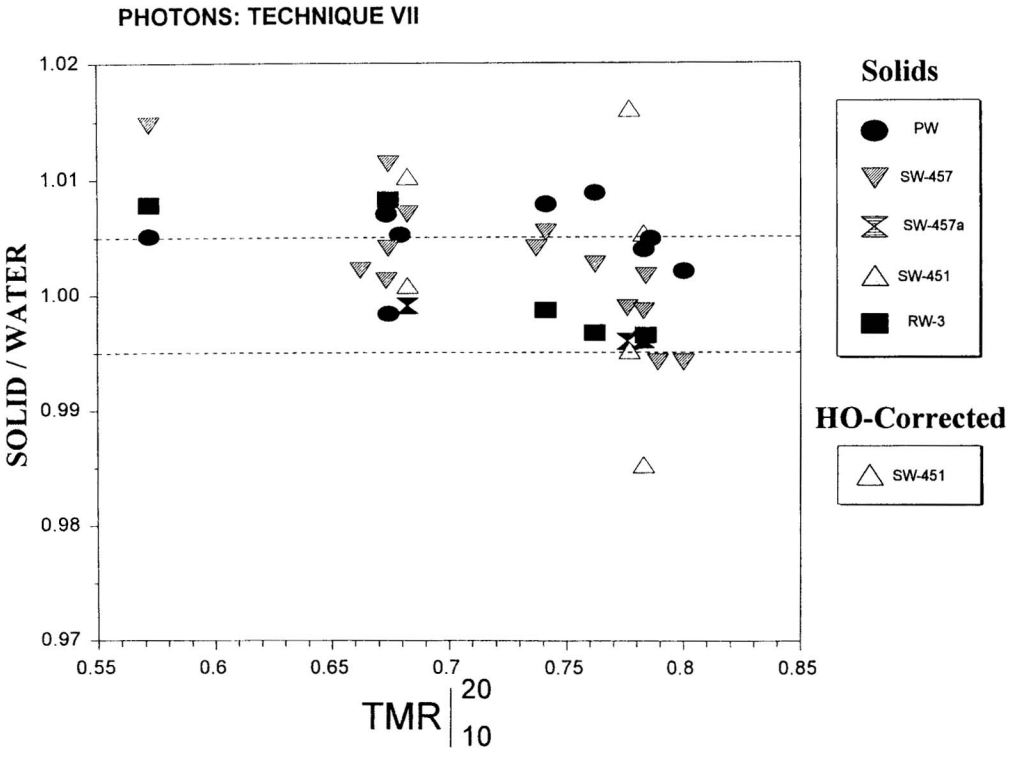

FIG. 7. The dose ratio, solid/water, as a function of $TMR|_{10}^{20}$ using technique VII. The measurements in solid were made at 5 or 7 g/cm^2 depth and the fractional depth ionization measured at 5 or 7 cm depth in water was used to determine d_{max}.

in data seen in this figure arises only from the consideration of the different materials and/or techniques presented in this work. There are other compounding factors which may increase the spread. Some of these factors are: mixing slabs of different materials by the user, inhomogeneities in the material, incorrect size and incorrect centering of probe cavity, incorrect-temperature measurements (see Sec. V), set-up errors, etc.

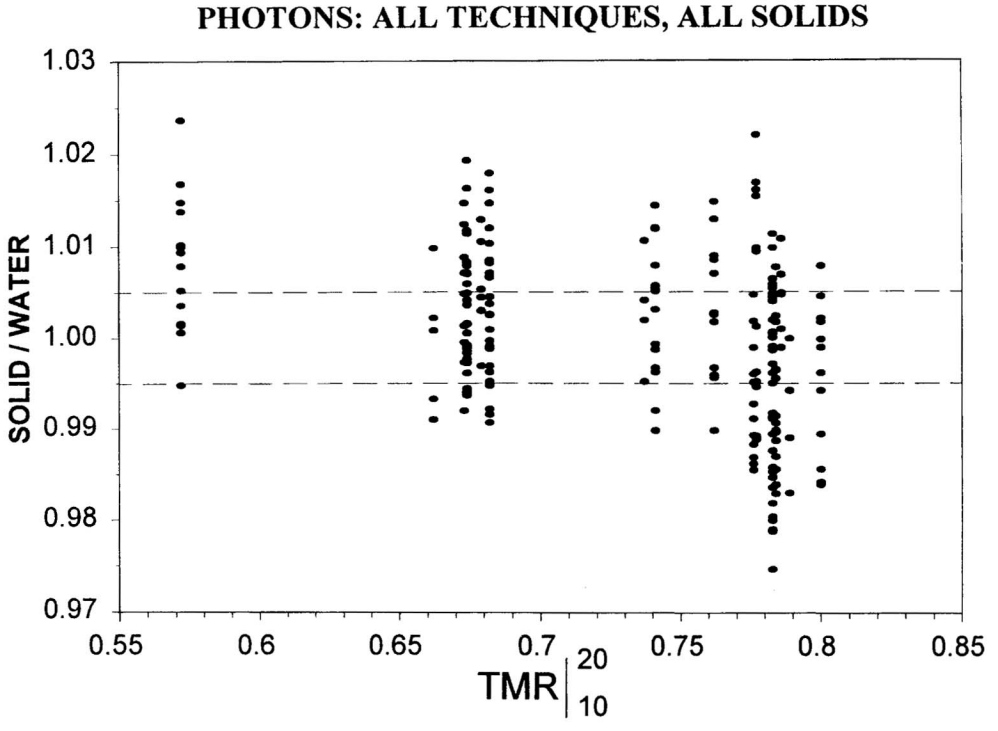

FIG. 8. The dose ratio, solid/water, as a function of beam energy ($TMR|_{10}^{20}$) for all combinations of techniques and solid phantom materials for photons.

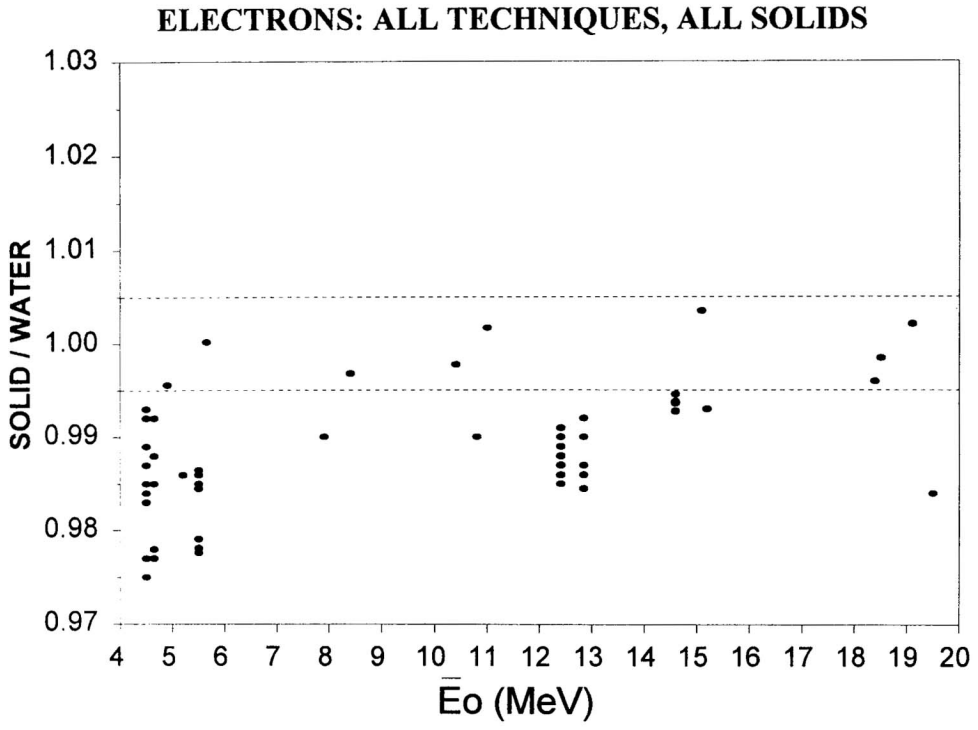

FIG. 9. The dose ratio, solid/water, as a function of beam energy ($\bar{E}_0$) for all combinations of techniques and solid phantom materials for electrons.

The recommended method for identifying beam quality or energy for both photons and electrons is to measure relative ionization at several depths. For photons, the comparison of percent ionization measured in solid phantom materials versus that in water is presented in Table VI. At 5 or 7 cm depth, all solid phantom materials show an agreement with water within 0.5%. The difference in percent ionization at the 5 or 7 cm depth versus that at the 5 or 7 g/cm^2 depth is about 0.3% for the PW, 0.4%–0.5% for SW451 and SW457a, and 0.9%–1.0% for RW3 and SW457. The difference seen for solid phantom material PW is small, primarily because its density is close to that of water. These differences would be larger at deeper depths, which users should measure at if these solid phantom materials are to be used for beam-energy characterization. For electrons, ionization measurements were made at various depths up to those exceeding 50% ionization (d_{50}) so that the d_{50} could be interpolated. For presentation purpose, the d_{50} are listed in Table VII. The agreement in d_{50} is representative of agreement in depth ionization at other depths. The d_{50} for all solid phantom materials show an agreement with water within 1 mm, excluding the solid phantom material SW457a that shows disagreement up to 3 mm.

There are limited data in the literature evaluating these materials. Reft[1] reports agreement between solid water and water within ±0.5% for photons when he uses Ho and Paliwal[2] interaction coefficient and "proper scaling." Prasad[15] reports values of solid/water ratio from 0.989 to 0.996 for 6 to 20 MeV electrons, respectively.

Al-Ghazi *et al.*[16] reports results within 1% between solid water and water for a wide range of photon and electron beams and Bank[17] reports solid/water ratios from 0.978 to 0.993 for 6 to 20 MeV electrons. None of these specify which model of solid water™ was used. Prasad and Bank show the same trend with energy that we have observed for electron beams and we do not reproduce Reft data for photon beams. However, the information concerning the measurement techniques in these references is limited, so that a fair assessment of the agreement or disagreement with our results is not possible.

VI. OBSERVATIONS

It is important to stress that when making measurements in solid phantom material phantoms, the temperature in the chamber cavity may be different from the temperature of the air in the room by several degrees. In addition, the temperatures of phantoms stored at different places in a treatment room may differ from each other and also from the air temperature near the treatment head. The practice of assuming that the air in the chamber inside a solid phantom material phantom is at room temperature can easily introduce dose discrepancies of up to 1% and has been seen by us to introduce dose discrepancies of up to 2%.

The procedure for commissioning solid phantom materials used as dosimetry phantoms should include assessment of the thickness and density of each slab, as well as the variation of thickness in a single slab or density between slabs, investigation (by radiograph) of bubbles or voids in the solid phantom material, warping, which may introduce an air gap between slabs, proper location of the chamber cavity, snugness of the cavity fit to the chambers and dose-output comparison with water. Other concerns of solid phantom material phantoms, not included here, are radiation damage, electron-

TABLE VI. Photon depth ionization results for solid phantom materials are compared with those for water.

Beam energy (MV)				% depth ionization					
Nominal	IR	Machine	Depth	Water	PW	RW-3	SW-457	SW-451	SW-457a
6×	0.662	Cl 6/100	5 cm (5 g/cm^2)	86.2	—	—	86.5 (87.4)	—	—
	0.673	Cl 2100	5 cm (5 g/cm^2)	86.9	87.5 (87.8)	86.9 (87.7)	—	—	—
	0.674	Cl 6/100	5 cm (5 g/cm^2)	86.6	86.8 (87.0)	86.8 (87.7)	—	—	—
	0.674	Cl 2100	5 cm (5 g/cm^2)	86.8	—	86.7 (87.6)	86.9 (87.9)	—	—
	0.679	KD	5 cm (5 g/cm^2)	88.3	88.8 (89.1)	—	—	—	—
	0.682	KD	5 cm (5 g/cm^2)	88.1	—	—	88.6 (89.5)	87.8 (88.3)	88.0 (88.4)
10×	0.741	MeV 74	5 cm (5 g/cm^2)	92.3	92.9 (93.1)	92.4 (93.2)	93.0 (93.9)	—	—
18×	0.776	KD	7 cm (7 g/cm^2)	89.9	—	—	90.4 (91.4)	89.8 (90.4)	—
	0.777	KD	7 cm (7 g/cm^2)	90.1	—	—	89.9 (91.0)	90.1 (90.6)	90.5 (90.9)
	0.783	KD	7 cm (7 g/cm^2)	90.7	90.8 (91.1)	—	—	—	—
	0.783	MeV 80	7 cm (7 g/cm^2)	90.4	—	—	90.6 (91.7)	90.8 (91.4)	91.3 (91.7)
	0.784	Cl 2100	7 cm (7 g/cm^2)	90.0	90.1 (90.6)	89.9 (91.0)	90.0 (91.1)	—	—
24×	0.800	Cl 2500	7 cm (7 g/cm^2)	92.9	93.2 (93.5)	—	92.7 (93.7)	—	—

storage problems,[14] and change of physical and chemical characteristics with time.

VII. CONCLUSIONS

For photons, none of the solid phantom materials consistently agreed on output calibration within 0.5% with water over all energies and all techniques. For electrons, only PW was within 0.5% of water for all energies. Since the density of PW is near unity, all five techniques reduced to one technique for electrons. All other solid phantom materials exceeded this 0.5% criterion. When all combinations of phantom materials, measurement technique, modality and energy were considered, the total spread in the data ranged from 2% to 2.5% for electrons and 3% to 5% for photons.

Most solid phantom materials showed an energy dependence for both photons and electrons. The solid/water ratio was less than unity, and it was lower for lower-energy electrons, approaching unity as the beam energy increased. This suggests that scattering powers are not properly matched, thus yielding a nonunity fluence ratio. For photons, the solid/water ratio was greater at lower energies than at higher energies. The absolute value depends on the technique, but the trend remained.

For electrons, the agreement in depth of 50% ionization with water suggests that the beam-energy characterization with these solid phantom materials is acceptable with a possible exception of the solid phantom material SW457a, which is not commercially available. For photons, discrepancy in depth ionization is up to 1% at 5 or 7 g/cm^2 depth.

TABLE VII. Electron depth ionization results for solid phatom materials are compared with those of water.

Beam energy (MeV)				Depth (cm) of 50% ionization				
Nominal	E_0	Machine	Water	PW	RW-3	SW-457	SW-451	SW-457a
6e	4.5	KD	1.9	—	—	2.0_5	2.0	2.1
	4.9	KD	2.1	2.2	—	—	—	—
	5.5	Cl 2100	2.4	—	2.4	2.4	—	—
	5.65	Cl 2100	2.4	2.4	—	—	—	—
12e	10.4	KD	4.4_5	4.5	—	—	—	—
15e	12.4	KD	5.3	—	—	5.5	5.4	5.6
16e	14.6	Cl 2100	6.3	—	6.3	6.3	—	—
20e	18.4	Cl 2100	7.9	7.8	—	—	—	—
	18.5	KD	7.9	8.0	—	—	—	—

With the percent ionization data measured only to limited depths for photon beams, we cannot comment on the energy characterization with the use of these solid phantom materials.

Before any solid phantom material is used as a water substitute, a comparison with measurements in water should be carefully performed, periodic checks at reasonable intervals might be also needed to assure the validity and consistency of the original comparison results.

ACKNOWLEDGMENTS

The authors wish to thank the Mayo Clinic (Rochester, MN), Baylor College of Medicine (Houston, TX), and University of New Mexico (Albuquerque, NM) for allowing us to take measurements on their therapy units. Our special thanks to Dr. Terrance N. Teslow, David M. Bellezza and Dr. Walter Grant III (Baylor College of Medicine), Dr. John Hazle (M. D. Anderson Cancer Center) and Kevin McCullough (Mayo Clinic) for performing confirmatory measurements with some photon and electron beams. This work was supported by PHS Grant No. CA 10953, awarded by the National Cancer Institute, DHHS.

[a]Present address and address for reprints: Department of Radiation Physics, Box 547, The University of Texas M. D. Anderson Cancer Center, 1515 Holcombe Blvd., Houston, TX 77030.

[1]C. S. Reft, "Output calibration in solid water for high energy photon beams," Med. Phys. **16**, 299–301 (1989).

[2]A. Ho and B. Paliwal, "Stopping-power and mass energy-absorption coefficient ratios for solid water," Med. Phys. **13**, 403–404 (1986).

[3]V. M. Tello, R. C. Tailor, and W. F. Hanson, "Evaluation of water-equivalent solid phantom materials for absorbed-dose calibrations of photon and electron beams," presented at the AAPM Southwest Chapter Meeting, October 9–10, 1992.

[4]V. M. Tello, R. C. Tailor, and W. F. Hanson, "Solid phantom materials for absolute dose calibration for photon and electron beams," abstract in Med. Phys. **18**, 643 (1991).

[5]V. M. Tello, R. C. Tailor, and W. F. Hanson, "Solid water solid phantom material as a calibration phantom for high energy photons and electrons," abstract in Med. Phys. **17**, 522 (1990).

[6]American Association of Physicists in Medicine, Radiation Therapy Committee Task Group 21, Med. Phys. **10**, 741–771 (1983).

[7]W. F. Hanson and J. A. D. Tinoco, "Effects of solid phantom material protective caps on the calibration of therapy beams in water," Med. Phys. **12**, 243–248 (1985).

[8]C. Constantinou, F. Attix, and B. Paliwal, "A solid water phantom material for radiotherapy x-ray and x-ray beam calibrations," Med. Phys. **9**, 436–441 (1982).

[9]American Association of Physicists in Medicine, Radiation Therapy Committee Task Group 25, Med. Phys. **18**, 73–109 (1991).

[10]R. C. Tailor and C. Chu, "Air temperature in the thimble of a Farmer type ion chamber," abstract in Med. Phys. **18**, 643 (1991).

[11]J. W. Boag, in *Radiation Dosimetry*, Vol. II, edited by F. Attix and W. Roesch, 2nd ed. (Academic, New York, 1966), Chap. 9, Sec. III.

[12]J. W. Boag and J. Currant, "Current collection and ionic recombination in small cylindrical ionization chamber exposed to pulsed radiation." Br. J. Radiol. **53**, 471–478 (1980).

[13]D. I. Thwaites, "Measurements of ionization in water, Polystyrene and a 'solid water' phantom material for electron beams," Phys. Med. Biol. **30**, 41–53 (1985).

[14]D. M. Galbraith, G. A. Rawlinson, and P. Munro, "Dose errors due to charge storage in electron irradiated plastic phantoms," Med. Phys. **11**, 197–203 (1984).

[15]S. C. Prasad, "Comparison of absorbed doses in water and solid water from electron beams," Med. Dosimetry **17**, 205–206 (1992).

[16]M. S. A. L. Al-Ghazi, I. Tavares, and B. Arjune, "On the dosimetric equivalence of solid water to water," abstract GG29, Med. Phys. **20**, 933 (May/June 1993).

[17]M. Bank, "Differences in electron beam measurements in water and solid water," abstract II35, Med. Phys. **21**, 963 (June 1994).