A solid water phantom material for radiotherapy x-ray and γ-ray beam calibrations

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The formulation, manufacture and testing of an epoxy resin-based solid substitute for water is presented. This "solid water" has radiation characteristics very close volumetrically to those of water. When it is used as a dosimetry phantom for x- and γ-ray beams in the radiotherapy range, phantom-to-water corrections and density corrections are eliminated. Relative transmission measurements have shown that the transmission through 10 cm of solid water is within 0.2% of that through an equal thickness of water for x and γ rays. The use of this material for calibration phantoms can help achieve the goal of radiotherapy beam calibrations within $\pm$ 1.0% of the true dose rate, easier to achieve.

I. INTRODUCTION

The protocols for the dosimetry of x- and γ-ray photon beams in the radiotherapy energy range, as well as for high energy electrons,[1,2] specify water as the standard reference material. If the phantom material used is not water but a plasticlike Lucite or polystyrene, corrections are suggested in order to determine the dose-to-water from the measurements. In practice, however, these corrections are often overlooked or applied incorrectly, leading to calibration errors.

Another cause of uncertainty in radiotherapy photon dose calibrations stems from the in-phantom use of ion chambers having walls and/or buildup caps differing in composition from the surrounding phantom medium. In that case, a fraction of the total ionization in the chamber cavity is produced by secondary electrons arising in the chamber wall and the remaining fraction of the total ionization is produced by electrons which come from the phantom medium.

The application of cavity theory to such composite material-wall situations has not been rigorously treated as yet. The well-known C_λ factor, which is used to obtain the absorbed dose in water from the chamber reading in phantom, is based on application of the Bragg–Gray theory, ignoring the presence of a "foreign" chamber wall material between the gas and the surrounding phantom medium. Kutcher *et al.*[3] have shown that the resulting error may be compounded by the recommendation of the SCRAD–AAPM protocol[2] that the buildup cap (usually Lucite) be used on the chamber in phantom.

Despite the need for the above corrections, convenience and/or geometric considerations often dictate the use of solid phantom materials as substitutes for water. The production of a solid substitute, which would have radiation absorption and scattering characteristics closely simulating those of water, would allow the use of solid phantoms without the accompanying errors. Dosimetry of photons and electrons would thus become simpler and more accurate. If the mechanical properties of that material were such that it could also be used for the manufacture of ion chambers and buildup caps, it would further improve the accuracy of radiotherapy beam calibrations. These developments would be particularly important at the many radiotherapy centers where routine calibrations are necessarily carried out by nonprofessional staff.

In the following sections a material will be described which we call "solid water" because its photon radiation characteristics are very close to those of water. The properties of solid water will be compared to those of water and other materials commonly used. The radiation characteristics of solid water are very close to those of water, not only in the radiotherapy beam range, but also for diagnostic x rays. Consequently, it can be used both for the production of radiotherapy beam calibration and standardization phantoms and for phantoms useful in general radiography and computed tomography. For electron beams, despite solid water being closer to water than are either Lucite or polystyrene, a slightly modified mixture will be necessary since the one described here gives transmission readings approximately 3% lower than those obtained with an equal thickness of water.

II. MATERIALS AND COMPOSITION OF SOLID WATER

Following the introduction of the "basic data" method for the simulation of tissue substitutes by White,[4,5] the method was applied to the simulation of water and as a result, an epoxy resin-based solid rigid substitute for water (*WT/SR* 1) was initially formulated and produced in the Radiation Physics Department of St. Bartholomew's Hospital, London EC1, U. K., as described by Constantinou[6] and White and Constantinou.[7] This material was comprised of epoxy resin,

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calcium carbonate, polyethylene, and phenolic microspheres. The epoxy resin system used as base material in the formulation is called *CB* 4, and its low-to-medium viscosity allows various particulate fillers to be thoroughly mixed in it. The slow curing rate (24–48 h required for complete solidification) and low exothermic heat generation permit the casting of 30×30-cm slabs up to 10 cm in thickness.

The specific gravity of the unfilled *CB* 4 system is 1.150 and the addition of fillers like calcium carbonate raise it to higher values. In order to reduce the specific gravity of the final product to that of the material being simulated, phenolic microspheres (PMS) are used in relatively small quantities. The components of *CB* 4 and its distributors, as well as the distributors of PMS in the U. S. and U. K., are given in Appendix A. More details about the composition, properties and availability of the above and other components have been provided elsewhere.[4,6,8]

The equipment needed for the production of the solid water and other epoxy resin-based substitutes consists mainly of a small vacuum pump able to reduce the ambient pressure to 1 mm Hg, a stirrer and a closed reaction vessel system. This equipment, as well as the manufacturing procedures, are also described elsewhere.[4,6,9,10]

The goal of the present work was more specific than that of the earlier cited papers. Solid water was formulated to be so closely "water equivalent" that the immersion of massive slabs of it into a water phantom will cause no significant change in the reading of a dosimeter in or behind the phantom penetrated by a radiotherapy photon beam of arbitrary dimensions. This requirement makes the specific gravity of the material as critical as its composition. As the specific gravity of the product depends, to some extent, on the batches of the raw materials used, most of the effort in this project was spent in mixing and testing several samples while making minor adjustments in the composition, to be discussed in the next section. With a good quality control program, which is essential in any effort to make this material, it has been found that solid water is more reproducible and a more satisfactory replacement for water than other materials employed before as water substitutes.

Table I shows the components and their percentage weights, as well as the elemental composition of the solid water sample *WT/SR* 6, typical of the final mixture. It can be seen that the optimum specific gravity is 1.5% greater than that of the water it displaces.

The slightly higher density of solid water was required in order to match the electron density of water (e/cm^3) and make it "volumetrically" equivalent to water so that transmission of x and γ rays through each one of them is the same, on a cm per cm basis. Figure 1 shows a stack of 30×30-cm slabs of solid water with varying thicknesses. The slab on the top has a hole cast to the dimensions of a 0.6-cm^3 Farmer-type ionization chamber, so that when the chamber is inserted, the center of its sensitive volume is located at the center of the 2-cm-thick slab of solid water.

TABLE I. Composition of solid water.

		Percentage by weight (sample *WT/SR* 6)
(a)	Components:	epoxy *CB* 4 (80.48), polyethylene (10.00), calcium carbonate (5.77), PMS (3.75)[a]
(b)	Elements:	H(8.09), C(67.22), N(2.40), O(19.84), Ca(2.32), Cl(0.13)
(c)	Specific gravity:	1.015 ± 0.002[b]

[a]Unsieved PMS.
[b]Relative to distilled water at 22 °C, which has a density of 997.8 Kg/m^3.

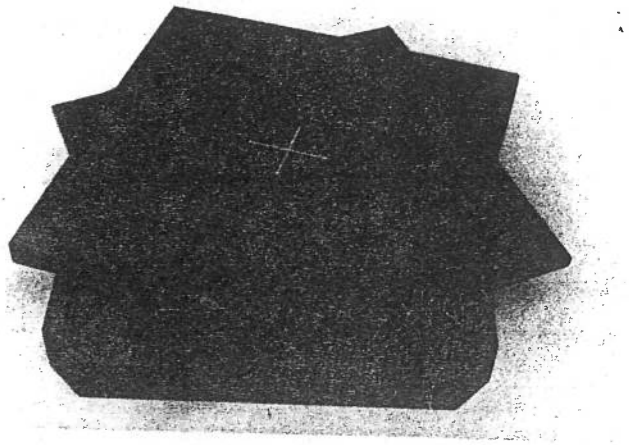

FIG. 1. The solid water calibration phantom.

III. EXPERIMENTAL AND THEORETICAL EVALUATION

The present work was carried out at the University of Wisconsin in collaboration with personnel at Radiation Measurements Incorporated, Middleton, WI. The objective was to further refine the manufacturing techniques of solid water and to investigate the effect of changing batches of resins and phenolic microspheres as well as the effect of using sieved (100 μ–200 μm) microspheres as opposed to unsieved ones (10–250 μm).

The reproducibility in the specific gravity among samples produced from the same batches of chemicals but on different days and by three different workers was also examined. Various samples of solid water were produced by varying only one of the above parameters at a time, and measurements were made of the specific gravity, transmission of radiotherapy photon beams relative to water, as well as the CT number of each sample.

In order to measure the transmission through each sample relative to water, readings (I) were first taken with a 0.6-cm^3 Farmer-type ion chamber placed on the central axis of a 10×10-cm horizontal cobalt-60 γ-ray beam in a 40×40×40-cm Lucite tank filled with distilled water. The front surface of the phantom was at 80-cm SSD and the chamber was placed at the phantom midpoint (Geometry A). Two 1-cm, two 2-cm, and one 4-cm-thick slabs of solid water, forming a 30×30×10-cm-thick stack, were then introduced into the tank, displacing an equal volume of water and the measurements were repeated with the solid water slabs touching the front (upstream) inner face of the tank, as shown in Fig. 2 (Geometry B). The solid water was also placed midway between the front face of the tank and the ion

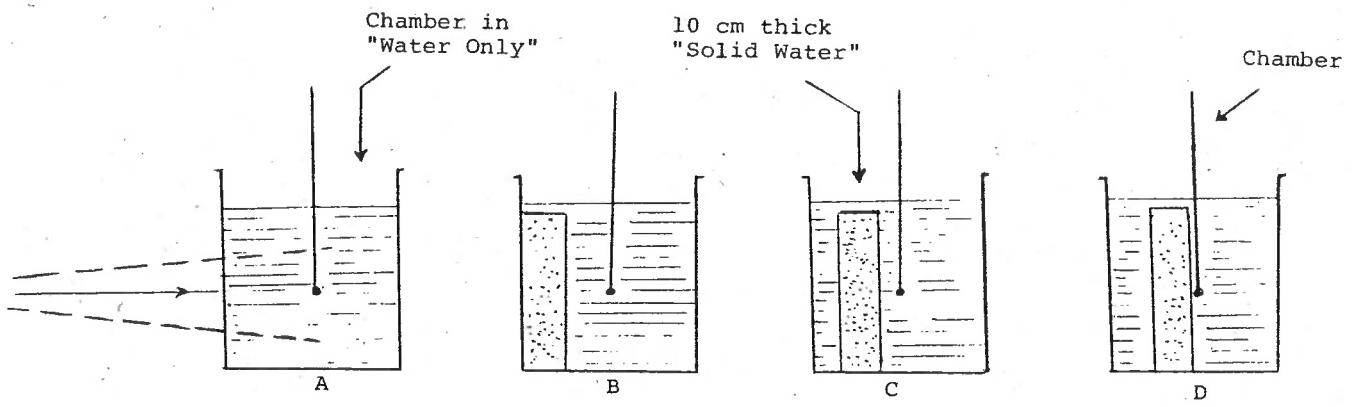

FIG. 2. Schematic diagram of the geometries used during the transmission measurements.

chamber (Geometry C) and, finally, just in front of the ion chamber (Geometry D). The readings obtained with the solid water in any of the above geometries were, within experimental error, the same since the difference between them never exceeded 0.3% of their average. Consequently, the reading I' was obtained by averaging the readings gotten with Geometries B, C, and D. The effect of each of the variables mentioned before on the transmission relative to water was evaluated by comparing the ratios (I'/I) obtained from measurements on different samples. The results are shown in Table II. Since the measurement of transmission relative to water was made with cobalt-60 γ rays under wide beam conditions ("poor"geometry), the effective attenuation coefficient may be approximated by the energy absorption coefficient (μen) in any low atomic number Z medium. Under this assumption, the μen of each sample of solid water can be calculated from the μen value for water, the thickness χ of each sample and the corresponding measured value of (I'/I), as is shown in Appendix B. Column 4 of Table II shows the observed maximum variation of $(\mu\text{en})_{\text{solid water}}$ from that of water for the various samples of solid water mentioned before.

In order to test the effect of the same parameter on the radiation characteristics of the solid water for x rays in the diagnostic range, an EMI 5005 general purpose CT scanner operating in the head mode was employed to measure the CT number of each sample. It was found that any sample produced from the same batch of chemicals had a CT number differing from the average by less than $\pm$ 1 CT number. The maximum difference observed between water and any solid water sample, irrespective of which resin or PMS batch was used, was 6 CT numbers. However, even in the worst case, it was always possible to modify slightly the formula in the right direction and produce a second sample which differed from water by less than $\pm$ 2 CT numbers.

The results of transmission measurements relative to water, using a 10-cm-thick stack of the solid water sample *WT/SR* 6 with x and γ rays in the radiotherapy energy range, are presented in Table III. Similar measurements for field sizes ranging from 5 × 5 cm to 20 × 20 cm, showed no field size dependence of these ratios. In the case of 12–18-MeV electron beams, the ion chamber was placed at a depth of 5 cm and a 3-cm-thick slab of solid water was placed immediately in front of the chamber.

A further comparison was made by measuring the percent depth doses along the central ray of a cobalt-60 beam, using a 10 × 10-cm field at 80 cm SSD and a 0.6-cm^3 cylindrical ion chamber in a 30 × 30 × 40-cm polypropylene tank, which had a 10-μm-thick mylar window and was filled with water; the measurements were repeated in the 30 × 30 × 30-cm solid water phantom using the same beam and geometry. The slab "hosting" the ion chamber (without buildup cap) was moved

TABLE II. Reproducibility of solid water.

Parameter changed	Maximum measured percentage variation ($\pm R$ %) Specific gravity	Transmission relative to water (I'/I)[a]	Linear energy absorption coefficient (μ_{en})	Maximum variation in CT number ($\pm$) (EMI 5005, 120 kVp)
(a) Resin batch	0.10	0.10	0.45	1
(b) PMS batch	0.60	0.60	2.30	6
(c) Sieved versus unsieved PMS	0.10	0.10	0.45	1[b]
(d) Mix on different days	0.10	0.10	0.45	1
(e) Increase PMS content by 0.1% by weight	− 0.20	+ 0.20	− 0.68	− 2

[a] For 10-cm-thick samples.
[b] Lower for unsieved PMS.

TABLE II. Transmission relative to water (10-cm-thick sample *WT/SR* 6, 10× 10-cm field).

Modality of energy	SSD (cm)	$\left(\frac{I' \text{ with plastic}}{I \text{ water only}}\right)$
Co-60 gamma rays	80	1.001 ± 0.001
4-MV x rays	80	1.002 ± 0.002
10-MV x rays	100	1.002 ± 0.002
12-MeV electrons[a]	100	1.031 ± 0.010
15-MeV electrons[a]	100	1.028 ± 0.008
18-MeV electrons[a]	100	1.037 ± 0.003

[a]Note that the geometry for these electron measurements differed from that used for the gamma rays (see the text).

along the stack in order to make measurements with the chamber at different depths in the phantom. The resulting depth dose curves were indistinguishable (see Fig. 3). A 0.5-mm error in positioning the chamber in the water phantom would introduce an uncertainty in the measured dose which, at 5 cm depth, was found to be $\pm$ 0.4% of D_{max}. The maximum discrepancy between the measured dose values in the two phantoms, at any depth, was of the same magnitude.

In a preliminary attempt to get an electrically conducting solid water for use in ion chamber walls, samples of "resin and graphite" mixtures, with graphite up to 15% by weight, were produced and tested. As the number of graphite grades is very large, the grade VULGAN XC-72 used by Shonka[11,12] in his conducting plastics was selected. The resulting samples were found to have a resistivity of $8 \times 10^4\ \Omega$ cm or greater, as compared to 100 Ω cm of the A-150 plastic used in the manufacture of ion chambers for neutron dosimetry. If adequate conductivity cannot be achieved, thin coatings of colloidal graphite can be used on the inside surface of solid water ion chambers.

The solid water dosimetry phantom was also evaluated theoretically by calculating its mass attenuation and mass energy absorption coefficients, as well as electron mass stopping and mass angular scattering powers and comparing

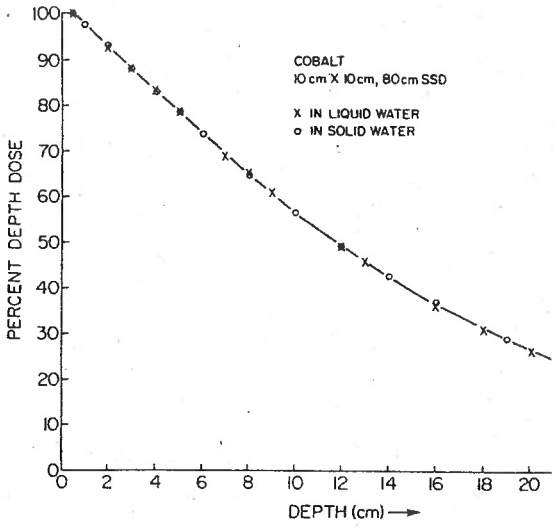

FIG. 3. Percent depth dose curve in solid water (O), and liquid water (×).

them with similar data for water at 33 energy points in the energy range from 10 keV–100 MeV, using the data and methods suggested by White.[4,13] Table IV shows the corresponding "coefficient ratios" and "stopping power ratios" for solid water/liquid water, at 0.01, 0.1, 1.0, 10.0, and 100 MeV.

Earlier experimental work has indicated that the use of polystyrene or Lucite phantoms can introduce errors in the measurement of the absolute dose which, in the case of electron beams can be as much as 5% at the point of dose maximum.[14,15] For comparison purposes, the radiation characteristics mentioned above were also calculated for polystyrene and Lucite and the corresponding ratios for polystyrene/water and Lucite/water are also given in Table IV.

IV. DISCUSSION

The use of a solid phantom makes dosimetric measure-

TABLE IV. Radiation characteristics of solid water (sample *WT/SR* 6), polystyrene and lucite, in the energy range 0.01–100 MeV.

	Material	Energy (MeV) 0.01	0.1	1.0	10	100
(a) Mass attenuation coefficient ratios	Solid water	1.05	0.97	0.97	0.96	0.91
	Polystyrene	0.41	0.95	0.97	0.93	0.83
	Lucite[a]	0.64	0.96	0.97	0.95	0.89
(b) Mass energy absorption coefficients ratios	Solid water	1.10	1.00	0.97	0.96	0.93
	Polystyrene	0.37	0.90	0.97	0.93	0.88
	Lucite	0.60	0.93	0.97	0.95	0.92
(c) Electron mass stopping power ratios	Solid water	0.97	0.97	0.97	0.97	0.95
	Polystyrene	0.98	0.97	0.97	0.95	0.89
	Lucite	0.97	0.97	0.97	0.95	0.89
	Material		0.01–100 MeV		SG Ratio	
(d) Electron mass angular scattering power and specific gravity ratios	Solid water		0.87–0.89		1.01–1.02	
	Polystyrene		0.78–0.80		1.02–1.05	
	Lucite		0.86–0.87		1.18–1.19	

[a]Lucite, Perspex, Polymethyl methacrylate.

ments easier and eliminates uncertainties in dosimeter positioning and problems of chamber waterproofing. However, since water is considered as reference phantom material, the use of common plastics like Lucite and polystyrene, whose radiation characteristics and density differ significantly from those of water, introduces errors that necessitate the use of a number of corrections if the measured absolute dose values are to be within $\pm$ 1.0% of the correct dose.

The new solid water phantom material proposed here, has been tested with cobalt-60 γ rays, 4 and 10-MV x rays, as well as a CT scanner operating at 120 KVp and found to have attenuation and scattering properties, on a volume-by-volume basis, very similar to those of water. Consequently, dose measurements in solid water require no corrections for composition or density differences from water.

With regard to dose measurements from electron beams in the radiotherapy energy range, although solid water is superior to both Lucite and polystyrene, it still requires a correction to account for the approximate 3% discrepancy observed between the properties of solid water and those of water. Although this discrepancy is smaller than the 4%–5% difference between doses determined from measurements in water and in polystyrene reported elsewhere,[14] the present solid water formula was optimized for photons rather than for electrons. It is evident that a separate "solid water E" for electron beams is needed, and it is our intention to modify the present formula for that purpose.

Repetitive calibrations of a radiotherapy beam using a tank filled with water imply that the ion chamber position has to be reproduced as accurately as possible every time. Observation of signal variations in repeated measurements with the chamber in the same position, indicated an uncertainty of $\pm$ 0.3% of the ionization at the depth of dose maximum. An error of $\pm$ 0.5 mm in the positioning of the chamber introduces an uncertainty in the measured absolute dose which, for Co-60 γ rays, 80 cm SSD, at 5 cm depth was found to be $\pm$ 0.4% of the maximum dose. The above uncertainties are minimized when a solid water phantom is used, because the positioning of the chamber in the phantom and subsequently at the same spatial point in the beam can be reproduced very accurately.

Comparative depth dose measurements in both liquid water and solid water using Co-60 γ rays and applying the same C_λ factor, temperature/pressure correction and chamber calibration factor indicated that the maximum discrepancy between the resulting depth doses was less than $\pm$ 0.5% of the maximum dose. When the measured depth dose data were plotted versus depth, there was no discernible difference between the two depth dose curves.

The maximum possible change in specific gravity and radiation characteristics of any two solid water phantoms can be observed if the phenolic microspheres used in the manufacture of the two phantoms come from different batches. As it has been demonstrated from quality control tests, however, once a sample is produced using any new batch of microspheres or resins and its specific gravity and attenuation properties measured, one can modify the percentage by weight of these components accordingly, so that all the phantoms produced subsequently from the same batch, give results within $\pm$ 0.2% of liquid water.

The matching properties of solid water are excellent and it can be used not only as phantom material, but also for the manufacture of ion chamber caps and ion chambers with the sensitive volume coated with graphite. Although the conductivity of the resin and graphite mixtures was found to be

The machining properties of solid water are excellent and it can be used not only as phantom material, but also for the manufacture of ion chamber caps and ion chambers with the sensitive volume coated with graphite. Although the conductivity of the resin and graphite mixtures was found to be 800 times smaller than that of the conducting plastic A-150, it might still warrant experiments to investigate whether this level of conductivity is adequate for dosimetric measurements. In that case, a modified solid water, with graphite as one of its components, could be used for the manufacture of ion chambers, although it is not clear at this time that that would be advantageous.

V. CONCLUSIONS

An epoxy resin-based solid substitute for water has been produced as a dosimetric calibration phantom material. This substitute has been called solid water and it has been compared to water both experimentally and theoretically, with x and γ rays of various energies and with electron beams in the radiotherapy energy range. Solid water was found to be superior to the commonly used Lucite and polystyrene phantoms.

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APPENDIX A

The epoxy resin system used as base material in the formulation of the solid water substitute is called *CB* 4 and it consists of two components, namely, 100 parts by weight Araldite MY750 and 40 parts by weight of the hardener XD716, both available from Ciba-Geigy Ltd., U. K. In the U. S., the first component is known as Araldite 6010, available from Ciba-Geigy Corporation, 444 Saw Mill Road, P. O. Box 430, Ardsley, NY 10502, tel. (914) 478-3131, while the second component is known as Jeffamine T-403, available from Jefferson Chemical Co., 336 Richmond Avenue, Houston, TX 77006, tel. (713) 666-8000.

Phenolic Microspheres (PMS type BJO 0930) are available from Union Carbide, 100 Ocean Gate, Long Beach, CA 90802, tel. (213) 435-3721. More details about the composition, properties and availability of the above and other components are given elsewhere.[6,8,9]

APPENDIX B

If I_0 = initial intensity of beam interacting with an X-cm-thick slab of a material and I = intensity of beam after it has passed through the slab, then, for X cm of water

$$\left(\frac{I}{I_0}\right)_{H_2O} = e^{-(\mu)_{H_2O}} X. \tag{1}$$

For a slab of solid water of the same thickness

$$\left(\frac{I'}{I_0}\right)_{\substack{\text{solid}\\ \text{water}}} = e^{-(\mu)\text{solid water}\cdot X}. \tag{2}$$

The logarithm of the ratio (I'/I_0):(I/I_0) gives

$$\ln\frac{I'}{I} = (\mu_{H_2O} - \mu_{\substack{\text{solid}\\ \text{water}}})\cdot X, \tag{3}$$

from which:

$$(\mu)_{\text{solid water}} = (\mu)_{H_2O} - \frac{\ln\left(\frac{I'}{I}\right)}{X}. \tag{4}$$

Assuming that under wide beam conditions (poor geometry), $\mu \approx \mu_{en}$, then Eq. (4) can be written as

$$(\mu_{en})_{\text{solid water}} = (\mu_{en})_{H_2O} - \frac{\ln(I'/I)}{X}, \tag{5}$$

where

$$(\mu_{en})_{H_2O} = \left(\frac{\mu_{en}}{\rho}\right)_{H_2O} \times \rho_{H_2O}$$

$$= \left[0.0296\ \frac{\text{cm}^2}{g} \times 0.9978\ \frac{g}{\text{cm}^3}\right]_{22\,^\circ\text{C}}$$

$$= 0.029\,53\ \text{cm}^{-1}.$$

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