Evaluation of water-equivalent plastics as phantom material for electron-beam dosimetry

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(Received 24 March 1994; accepted for publication 5 December 1994)

This investigation evaluated samples of three phantom materials designed as substitutes for water for electron beam calibration and depth ionization measurements. Two of the materials are commercially available (photon–electron Solid Water and Plastic Water), while the third (Homat) is not. Applying the values for water for all factors used in the calibration protocol of the American Association of Physicists in Medicine [Task Group 21, Med. Phys. **10**, 741–771 (1983)] results in a discrepancy in calculated peak dose rates. Eliminating this discrepancy requires the additional inclusion of a multiplicative correction factor of approximately 1.015 for beam energies below 10 MeV, 1.01 for beam energies between 10 and 12 MeV, and 1.005 for beam energies above 12 MeV. Measurements for R_{50} and extrapolated range may be made in these materials with no corrections. Some improvement can be made in the performance of the phantom material by optimizing the match to water specifically for electron beams without regard for photon beam response. As with all radiation oncology apparatus, calibration phantoms need acceptance testing before routine use.

Key words: phantoms, electron dosimetry, calibration

I. INTRODUCTION

The original epoxy resin-based phantom material known as Solid Water, reported by Constantinou,[1] was formulated using the "basic data method" described by White,[2] and used as a solid substitute for water for dosimetry with photon beams, and in the manufacture of phantoms useful in diagnostic radiology. Constantinou, Attix, and Paliwal,[3] evaluated the original formula Solid Water, and reported on the equivalence between water and Solid Water for transmission of photon beams. Thwaites[4] also evaluated the original Solid Water™ material (RMI model SW451; Solid Water™ Radiation Measurements, Inc., Middleton, WI 53562) as a substitute for water for electron-beam calibrations, and found that, while better than polystyrene, Solid Water was "still significantly different from a true water phantom." To address the electron-beam measurement discrepancies, Constantinou[5] intended to produce an electron solid water formula, but the advantage of having one phantom material for both photon- and electron-beam calibrations prevailed. Constantinou developed a new Solid Water formula, known as Solid Water for photons and electrons (RMI model SW457). Reft[6,7] published an evaluation of calibrations performed in photon–electron Solid Water compared to water, polystyrene, and acrylic for photon beams between cobalt-60 and 24 MV, finding that the dose rates measured in Solid Water fell between ±0.5% of those measured in water, using the values for the mean restricted mass stopping-powers and mean mass energy-absorption coefficients for Solid Water published by Ho and Paliwal.[8]

Tello, Tailor, and Hanson[9] reported the results of measurements in the original and photon–electron Solid Water and suggested the use of an electron fluence factor greater than unity, and possibly using stopping-power ratios for photon–electron Solid Water to improve the accuracy of electron-beam calibrations using this material. While tables of restricted mass stopping powers for various energies are not available for Solid Water, the developers intended the material to simply replace water, using the dosimetry factors for water in the calibration calculations. A later article by these same authors,[10] a report by Prasad,[11] and work by Al-Ghazi, Tavares, and Arjune[12] reaffirmed the conclusions.

A different, flexible solid material has recently become available (Plastic Water™, Computerized Imaging Reference Systems, Inc., Norfolk, VA, marketed by Victoreen/Nuclear Associates, Carle Place, NY 11514-0349), similarly based on White's approach. Tello *et al.*[13] evaluated this material and found that for electron beams the peak depth calibration matched water to within 0.4%, and the depth to selected fractional depth dose line matched to within 1 mm. Tailor, Tello, and Hanson[14] compared the equivalency of several water-equivalent plastics for calibration using the American Association of Physicists in Medicine (Task Group 21) protocol,[15] and found errors of 1% to 2.5% when using the solid phantoms.

Similar principles were used by Ho[16] to design another epoxy-based water substitute, referred to as Homat, which would give the same reading at peak depth as in water, by matching the stopping power and scattering power of water, without regard to the material's photon-interaction properties. Although not commercially available, Radiation Measurements, Inc., produced samples of this material for experimental testing purposes.

This report addresses the use of the water substitutes for electron-beam calibrations in a unified investigation, assesses

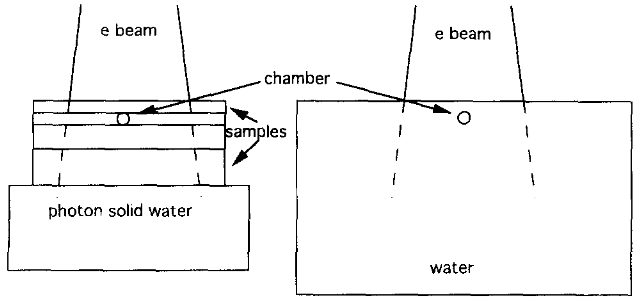


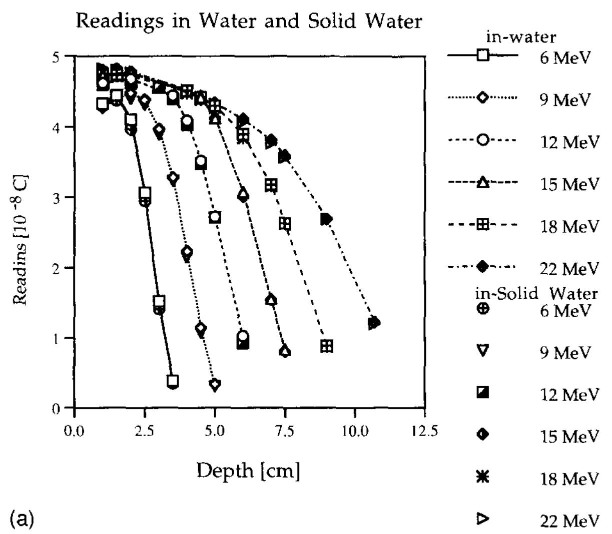
FIG. 1. Experimental setup.

the need for an electron fluence factor other than 1, and reviews the adequacy of the solids for fractional depth ionization (FDI) measurements, assuming the use of calibration factors for water.

II. MATERIALS AND METHODS

Duplicate sets of measurements were made in water and the water substitutes at various depths. The measurements for Solid Water and Plastic Water utilized identical instrumentation (PTW 0.6 cc Farmer Chamber, Model 23333-30; -300 V collecting bias; Keithley 602 electrometer; Fluke DMM, model 8060A) with a reproducibility of better than 0.3%. The electron beams came from a Varian Clinac-2500 (100-cm SSD; 10×10-cm^2 cone), with the electron energies (nominally 6, 9, 12, 15, 18, and 22 MeV) set such that the mean incident energy for each beam matched the nominal value to within ±0.1 MeV. All measurements were corrected for temperature in the respective phantom and atmospheric pressure, and the chamber allowed to equilibrate in each phantom until readings showed no monotonic changes in readings indicative of thermal changes. The 30×30 cm^2 slabs represented the chemical formulas in use at the time of writing. A Therados RFA300 facilitated setting the chamber depth in the water phantom, giving an uncertainty in depths of approximately 0.5 mm. The uncertainty in depth for the solids was less than 0.5 mm. A 0.18-mm latex sheet covered the chamber when in water.

Because the dosimetric factors for water are to be used with calibrations in the solid materials, the accuracy of a calibration in the water substitutes simply equals the difference between the readings in the solid to that in water for the same conditions. The evaluation at each depth consists of



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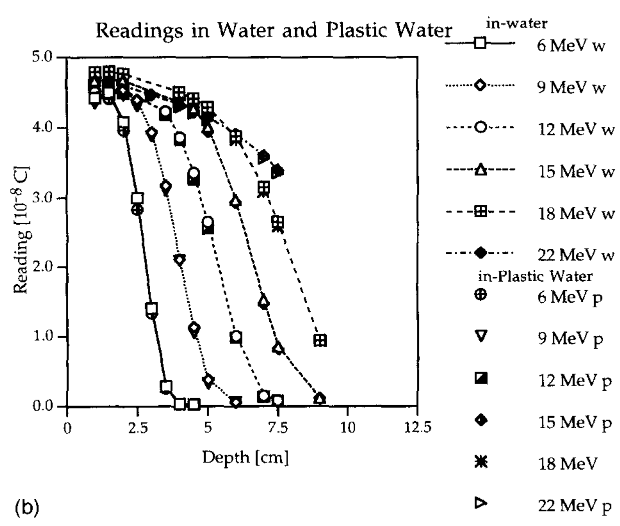

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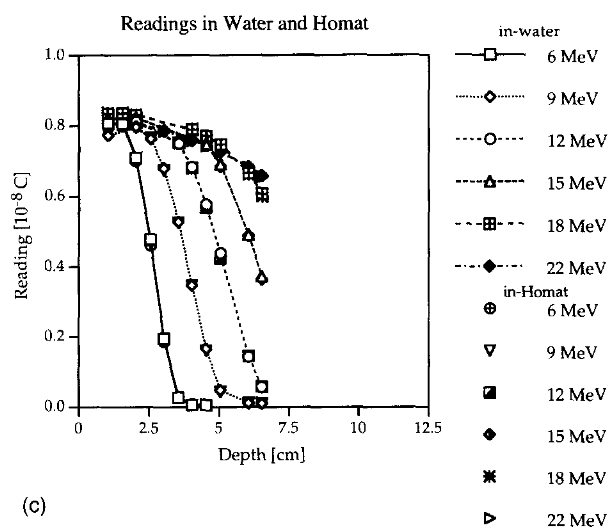

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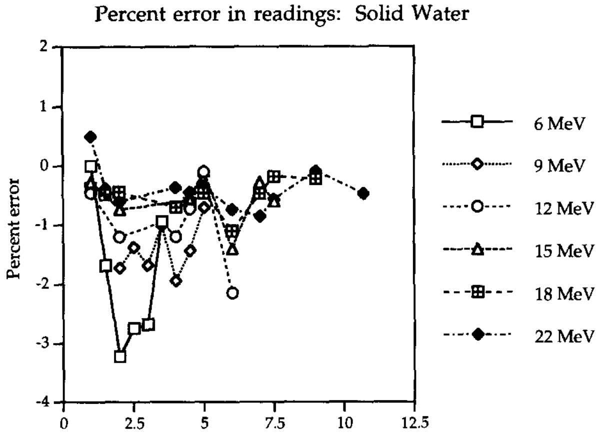
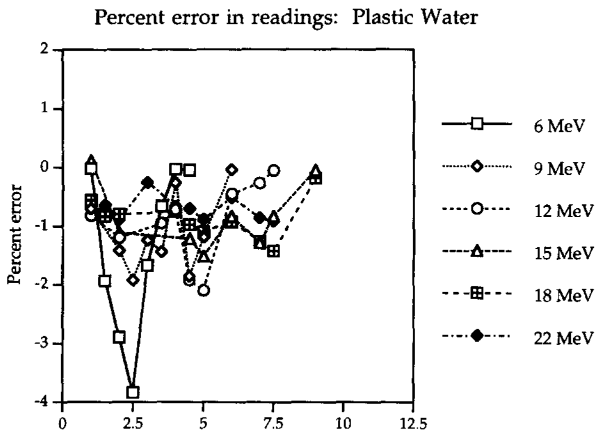
FIG. 2. Readings (in 10^{-8} C) taken in water (connected symbols) and in a plastic surrogate (unconnected symbols): (a) in Solid Water; (b) in Plastic Water; (c) in Homat.



(a)



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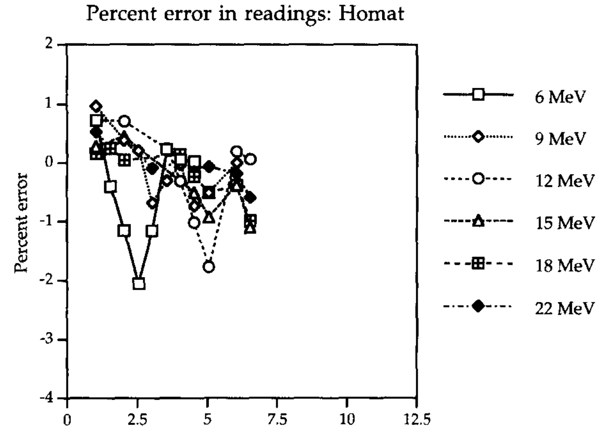


(c)

FIG. 3. Error in the readings in the solid phantom material as a percentage of the peak dose in water: (a) in Solid Water; (b) in Plastic Water; (c) in Homat.

this difference, and also of a comparison of the fractional depth ionization (FDI).

The entire experiment was repeated using Homat. Measurements in this material, and the corresponding measurements in water, used a PTW 0.37 cm^3 intracavitary chamber instead of a Farmer chamber. In all other respects the experiment remained the same as that with the other two phantom materials.

In all of the measurements made in a solid phantom, the phantom material rested on at least 10 cm of the original Solid Water to provide a uniform backscattering environment. The deepest reading for Plastic Water and Solid Water had 1 cm of the test material between the center of the chamber and the original Solid Water; the deepest reading with Homat had 0.5 cm behind the chamber center before the original Solid Water. The maximum depth of measurement in each material was dictated by the total thickness of the material available for the measurement. Figure 1 illustrates the experimental setup.

TABLE I. Percent difference in the peak depth reading in the solid materials compared to water (uncertainty $\leq 0.3\%$).

Energy (MeV)	Solid Water	Plastic Water	Homat
6	−1.6	−1.9	−0.4
9	−1.7	−1.4	0.4
12	−1.2	−1.2	0.7
15	−0.7	−1.2	0.4
18	−0.4	−0.8	0.0
22	−0.4	−0.6	0.3

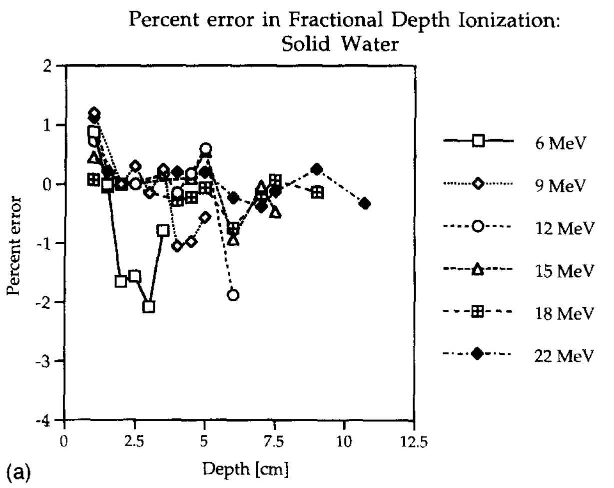
III. RESULTS

Figure 2 displays the readings taken in the solid materials superimposed on those taken in water. Given that the solids allowed only discrete depths, "peak values" were taken as the highest readings measured. The corresponding "peak values" for the water measurements used the identical depth as in the solids, rather than searching for the true peak. Figure 3 shows the error in the readings as a percentage of the peak reading for each energy, taken as

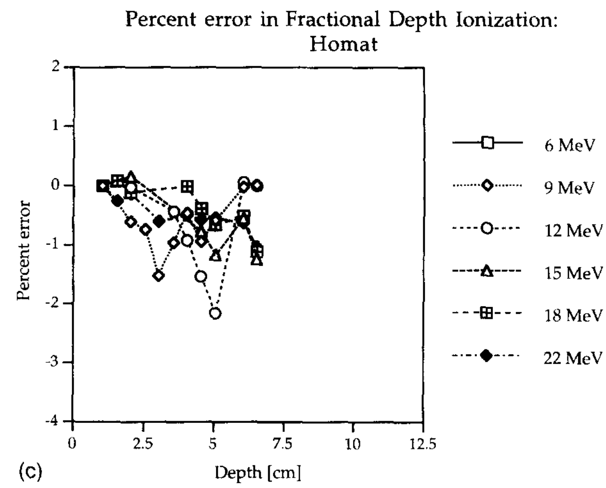
Percentage error

$$= \frac{(\text{reading in solid})-(\text{reading in water})}{(\text{peak reading in water})} \times 100$$

assuming that this usually is the quantity of interest, rather than



(a)



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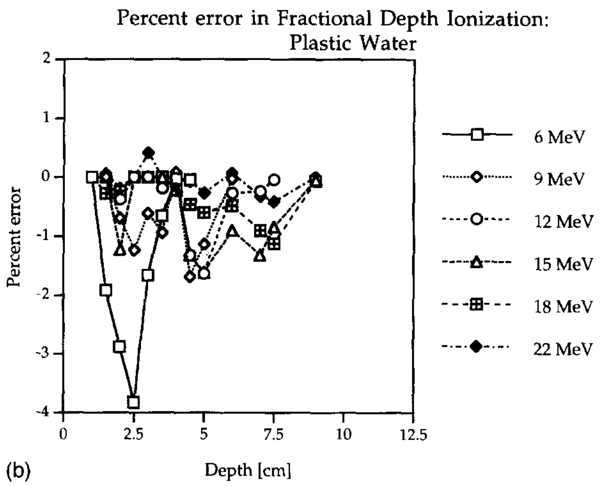

(b)

FIG. 4. Error in the fractional depth ionization (FDI) as the difference between the measured FDI in the solid and that in water, times 100: (a) in Solid Water; (b) in Plastic Water; (c) in Homat.

Percentage error

$$=\frac{(\text{reading in solid})-(\text{reading in water})}{(\text{reading in water})}\times 100.$$

In the latter equation, the absolute error becomes large as the readings become small.

The readings at the peak depth, both in Plastic Water and Solid Water show the same response: readings about 1% to 2% low for 6 and 9 MeV, and 0.5% to 1% low for 12 through 22 MeV. The Homat peak readings matched water slightly better, being approximately 0.5% low for the 6 MeV and around 0.5% high for the remainder of the beams. Table I summarizes the results at peak depth. For each of the experiments, the uncertainty for the ratio of the readings at peak depths is believed to be less than 0.3%.

In general, the readings in Solid Water and Plastic Water stay between 0% and −2% of that in water. The readings in Homat start slightly higher than those in water (between 0%

TABLE II. Reported comparisons of peak dose calibrations measured in water and plastic water equivalents. Values show dose measured in plastic divided by that measured in water.

Authors	Date	Electron–photon Solid Water MeV			Plastic Water MeV			Homat MeV		
		6–9	10–13	14–22	6–9	10–13	14–22	6–9	10–13	14–22
Tello *et al.*	1990	0.974		0.988						
Tello *et al.*	1992				0.998	1.002	1.003			
					0.996	0.998	0.999			
Prasad	1992	0.989	0.990	0.997						
Al-Ghazi *et al.*	1993	0.991	0.994	0.998						
Current work	1994	0.983	0.988	0.995	0.983	0.989	0.992	0.996	0.993	0.998
Constantinou *et al.*	1994	0.990	0.999	1.001						

and +1%) at 1-cm depth, but then slowly decrease with depth to around −0.5% at 6.5 cm. For both the Solid Water and the Plastic Water, the error only exceeds 2% for the 6-MeV beam around 2–2.5 cm deep, where the maximum error of approximately 4% falls. While not as large, the Homat curve shows a similar discrepancy at that depth. While the points at 2.0 and 2.5-cm depth fall in the steep gradient of the 6-MeV curve where the uncertainty in the depth could result in reading errors on the order of 3%–4%, the 2-cm deep point rests on the shoulder of the depth-ionization curve for the 9 MeV and higher energy beams. The entire experiment was repeated for the Solid Water and Homat, with the same results.

Figure 4 compares the fractional depth ionization (FDI) as measured in the solids to that measured in water. As would be expected, the patterns follow those for the errors, except normalized for the differences in peak readings. The uncertainty of 0.5 mm in positioning at the 90% FDI could result in a 1% error. As described above, a small error in depth produces large discrepancies in the steep-gradient portion of the FDI curve. That such large discrepancies were not seen tends to reinforce that the solids correctly model water and that the geometry avoids large errors.

A sample of Solid Water with a hole cut to accept a Farmer chamber with a ^{60}Co buildup cap attached was tested in the same manner as described above. Using correction factors for the effects of the cap at buildup as suggested by Hanson and Tinoco[17] for the readings at peak depth yielded results very similar to those reported above. For depths greater than peak depth, no correction values exist, and the differences in the readings become very large (several percent at midrange depths). For this reason, phantoms with such holes should be avoided for fractional depth-ionization measurements, or buildup caps made of material matching the phantom should be used.

Within the uncertainty of the experiment, the performances of Solid Water and Plastic Water appear comparable.

IV. DISCUSSION

The AAPM calibration protocol calls for measurements (a) at peak depth for dose rate determination, (b) at the depth where the ionization readings fall to half of the peak readings (R_{50}) to establish the initial energy of the electron beam, and (c) along the falling gradient and bremsstrahlung tail to establish the extrapolated range. Peak ionization measurements in Solid Water and Plastic Water appear to consistently underestimate the readings in water by approximately 1.5% for the 6- and 9-MeV beams, and 1% or less for the higher-energy beams. Table II summarizes some of the investigations of these discrepancies. The results of Tello *et al.*[9] and Tello *et al.*[13] were based on essentially the same geometry as used in this experiment, except for phantom size, using 20×20 cm^2 slab. For Solid Water, the consensus tends to verify a 1.5% under-response for electron energies below 10 MeV, and less than a 1% under-response above 14 MeV. Our investigation of Plastic Water yielded results indistinguishable from those for Solid Water, considering the uncertainties of the experiment. Tello *et al.*[9] suggested the use of that quantity referred to in the calibration protocol of the American Association of Physicists in Medicine[15] as the electron fluence correction in order to produce "correct" calculated dose rates. While this might be true were the actual stopping power for the plastic phantoms used, applying the values for water renders the factor a "general correction" factor. Regardless of which factors should change, the differences between the readings in water and the substitutes are consistent enough to be handled by a three-value constant with values of 1.015 below 10-MeV initial energy, 1.01 for beam energies between 10 and 12 MeV, and 1.005 above 12 MeV. Such a correction would yield dose rates within a few tenths of a percent of those measured in water. Measurements in a material such as Homat require a correction of approximately 1.005 for 6 MeV, and 0.995 for higher energies. Table II also includes the results of a separate evaluation of a different batch of Solid Water by one of the authors and co-workers.[18] The difference indicates that variations between batches may account for the various results of different investigators. The variations also lead to the suggestion that any phantom material should undergo acceptance testing for water equivalency (or the determination of correction factors) prior to clinical use.

The FDI measured in any of the solid phantoms predicts R_{50} values to within ±1 mm of those measured in water, which would result in calculated incident energies within ±0.2 MeV. As shown previously,[3–7] Solid Water mimics water for high-energy photons, so the bremsstrahlung tail should remain invariant in the two media. Construction of the falling portion of the FDI curve for extrapolated range determination using the solids matches that measured in water better than the determination of R_{50}. The extrapolated range enters the calibration protocol in the calculation of the actual electron energy at the position of the ionization chambers at peak depth, to establish the value for the replacement correction, p_{repl}. This factor varies slowly with the energy of the beam at the calibration depth, and thus, small errors in ionization chamber readings in determining the extrapolated range make little difference in the final, calibrated dose rate.

The under-response of the commercial plastics follows from their design. The original Solid Water was formulated to match the radiation characteristics of water for photons within 1% over a wide energy range. As it was later found to be less attenuating than water for electron beams, the density of the initial formula was modified to better match the electron stopping powers over the range of energies used in radiotherapy. The resulting electron–photon Solid Water has mass angular scattering powers that differ from water by more than 2%, resulting in the underestimation of dose at peak depth. It is not possible to improve the mass angular scattering power match with respect to water without changing the components of the material. The Homat formula has higher atomic-number elements added to bring its mass angular scattering powers closer to that of water; however, the photon attenuation characteristics of Homat are not as close to those of water as Solid Water, particularly at lower photon energies. At present, no reformulation is planned for any of the materials.

V. CONCLUSION

Commercially available photon–electron Solid Water and Plastic Water can be used as a substitute for water for electron-beam calibration using the values for all calculated factors appropriate for water except for the additional inclusion of a multiplicative correction factor of 1.015 for beams below 10 MeV, 1.01 for beam energies between 10 and 12 MeV, and 1.005 for beams above 12 MeV. Measurements for R_{50} and extrapolated range may be made in these materials with no corrections. Some improvement can be made in the performance of the phantom material by optimizing the match to water specifically for electron beams without regard to photon beam response. Acceptance tests on newly obtained phantom material prior to clinical use would be well advised.

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