Technical Note: Influence of entrance window deformation on reference dosimetry measurement in various beam modalities

Naoki Kinoshita[1, 2], Ryosuke Kohno[3], Hiroshi Oguchi[1]

[1]Department of Radiological and Medical Laboratory Sciences, Nagoya University Graduate School of Medicine, 1-1-20, Daiko-Minami, Higashi, Nagoya 461-8673, Japan

[2]Radiological Center, University of Fukui Hospital, 23-3, Matsuoka-shimoaizuki, Eiheiji, Fukui 910-1193, Japan

[3]Medical Physics Section, National Institute of Radiological Sciences, 4-9-1 Anagawa, Inage, Chiba 263-8555, Japan

Running title: Phantom window deformation

Corresponding Author

Naoki Kinoshita

Radiological Center, University of Fukui Hospital

23-3, Matsuokashimoaituki, Eiheiji-cho, Yoshida-gun, Fukui-ken 910-1193, Japan

Phone: 81-776-61-3111

Fax: 81-776-61-8154

Email: kinosita.naoki@gmail.com

Abstract

Purpose: Phantoms for horizontal-beam geometry can avoid issues in vertical-beam geometry, such as change in chamber depth due to evaporation, and defining the origin at the water surface. However, their thin entrance-windows would deform when these phantoms are filled, which can change the chamber depth, as pointed out by IAEA TRS-398. Currently, few reports [Arib *et al*., J. Appl. Clin. Med. Phys. **7**, 55–64 (2006), and Kinoshita *et al*., Rep. Pract. Oncol. Radiother. **23**, 199–206 (2018)] are available with practical data on window deformation. Therefore, we investigated the influence of entrance-window deformation on chamber depths in water phantoms and the measurements in various beam modalities.

Methods: To examine widely used phantoms and phantoms with different characteristics, three phantom types were investigated (the number of phantoms investigated appears in parentheses): PTW—type 41023 (2), Qualita—QWP-04 (2), and IBA—WP34 (2). Prior to the investigation, these phantoms were stored for acclimatization in a room for approximately 10 h under the following two conditions: (1) room temperature: 21 ± 2 °C; (2) room temperature: 27 ± 2 °C. Using a dial indicator, the centers of the windows were monitored every 30 min for 12 h immediately after the phantoms were filled, in a treatment room at the room-temperature of 21 ± 2 °C.

Results: Immediately after the phantoms were filled, the window deformation ranged from −0.07 (inward-deformation) to 0.3 mm (outward-deformation) among the six phantoms, in comparison with empty phantom windows. For 12 h after the phantoms were filled, the change in the deformation was up to 0.23 mm, but typically less than 0.15 mm.

Conclusions: Reference dosimetry in photon, electron, and proton beams would not be influenced significantly by these window behaviors, whereas the window deformation has a slight impact on those in heavy-ion beams.

Keywords: water phantom, horizontal beam geometry, entrance window deformation, ion chamber depth

Introduction

Water phantoms for horizontal beam geometry are used for the dosimetry of various beam modalities, such as high-energy photon-, electron-, proton-, and heavy ion-beams, in radiotherapy clinics. These phantoms have the ability to accurately position an ion chamber at a desired depth during measurements.[1] However, because their entrance windows are typically thin, operators may need to pay attention to the window deformation of the entrance windows when the phantoms are filled, which can change the chamber depth and source-surface distance, during the measurements.[2,3]

To the best of our knowledge, thus far, entrance window deformation has been poorly documented.[2-4] The most likely reason for this may be that the influence of the entrance window deformation on the radiation dosimetry uncertainty may be much lower than that of the other components that influence the radiation dosimetry uncertainty. Is it not therefore worth further study? The following publications have mentioned the window deformation effect. IAEA TRS-398 notes that, "A window of only a few mm in thickness may bow outwards slightly due to water pressure on the inner surface. Any such effect should be accounted for when positioning the chamber at the depth of interest, particularly in low-energy electron beams.[2]" Another publication states that, "This effect, which occurs as soon as the phantom is filled and which depends on the size of the phantom and the window, can change the chamber depth and the SSD considerably[3]". Although the two publications indicated that operators should be careful of the window deformation behavior during measurements, they did not specifically show the level of window deformation. The practical data on the outward bowing behavior may further aid in eliminating the possibility of inadvertent error in the chamber depth during measurements.

The problem statement in this work is, "How does the window deformation influence the chamber depth in a water phantom for horizontal beam geometry and reference dosimetry in various beam modalities?" Therefore, the purpose of this work was to provide practical data on the outward bowing behavior as a function of time elapsed up to 12 h, immediately after the phantoms were filled.

Materials and Methods

Water phantoms investigated

Three types of phantoms with different characteristics (e.g., window thickness and phantom size) from PTW (Freiburg, Germany), IBA (Schwarzenbruck, Germany), and Qualita (Nagano, Japan) were examined in this work (the number of phantoms investigated appears in parentheses) to evaluate the window deformation for type-to-type variability and phantom-to-phantom variability of the same type: PTW—type 41023 (2); IBA—WP34 (2); and Qualita—QWP-04 (2). When clinical medical physicists use a phantom for horizontal beam geometry for reference dosimetry, they generally select commercial water phantoms, such as PTW, IBA, and Qualita. Particularly, many clinical physicists can choose PTW and IBA phantoms because the two types of phantom are commercially available in many countries. We therefore examined three types of phantoms with different characteristics, including the PTW phantom and IBA phantom. The characteristics of these phantoms are listed in Table 1.

Experimental setup

Generally, water phantoms used in radiotherapy clinics are stored in the treatment room, cabinets, or remote areas. Their room temperatures could be different. To simulate the difference in temperature in those storage environments, the empty phantoms investigated here were stored for approximately 10 h under the following two conditions prior to the assessment of the entrance window behaviors: (1) a cool room: approximately 21 ± 2 °C; (2) a warm room: approximately 27 ± 2 °C. On the other hand, water that went into the empty phantoms was stored for more than 24 h in a treatment room for testing the deformation behaviors of their entrance windows. Then, the temperature in the treatment room was maintained at approximately 21 ± 2 °C.

Thereafter, for testing the deformation behaviors of the entrance windows, the phantoms were moved from the storage room to a treatment room just before the window deformation behavior was measured. During the measurements, the air temperature in the treatment room was maintained in the approximate range of 21 ± 2 °C by using an air conditioning system.

The temperatures and relative humidity in the storage room and the treatment room were monitored using the MHT-381SDJ humidity and temperature meter (Sato

Shouji, Kanagawa, Japan) with a resolution of 0.1% and 0.1 °C, respectively. This work, conducted during the autumn and winter months in our institution, did not involve relative humidity control. Consequently, the relative humidity over the course of this work was sometimes below 20% in the storage room (warm room).

Figure 1 shows the window-deformation measurement setup. We performed the assessment of the window deformation behavior with an ID-S112SB dial indicator (Mitsutoyo Corporation, Kanagawa, Japan) with a resolution of 0.001 mm. The centers of the entrance windows were monitored every 30 min for 12 h, beginning from the time just after the phantoms were filled, as shown in Fig. 1. When the phantoms were empty, we assumed the level window deformation (empty) to be a zero value. Each entrance window was measured under nearly the same conditions on several days to check repeatability. The water temperatures in the phantoms were measured with the SK-1250MCIIIα digital thermometer (Sato Shouji, Kanagawa, Japan) with a resolution of 0.1 °C, and were approximately 21 ± 2 °C, which is within ± 1 °C of the treatment room temperature.

Results

Window deformation immediately after the phantoms were filled

Figure 2 shows behaviors of the six phantoms' window deformations as a function of time elapsed until 12 h after the phantoms were filled. This figure shows that the entrance windows deformed as soon as the phantoms were filled. Immediately after the six phantoms were filled, the deformation levels varied: 0.04–0.32 mm for the two PTW phantoms; −0.07–0.15 mm for the two IBA phantoms; and −0.04–0.29 mm for the two Qualita phantoms (the negative values indicate that the windows bowed inward, whereas the positive values indicate that the windows bowed outward) depending on the phantom type, phantom-to-phantom of the same type, and the room temperature in the storage location.

Window deformation behavior after the phantoms were filled

After the six phantoms were filled, the entrance windows bowed outward with time, as shown in Fig. 2. Twelve hours after the phantoms were filled, the window deformations were as follows: 0.20–0.29 mm for the PTW phantoms stored in the warm room; 0.37–0.40 mm for the PTW phantoms stored in the cool room; 0.06–0.17 mm for the IBA phantoms stored in the warm room; 0.10–0.21 mm for the two IBA phantoms stored in the cool room; 0.12–0.19 mm for QWP-04 stored in the warm room; and 0.24–0.32 mm for QWP-04 stored in the cool room.

Figure 3 shows window deformation changes per 30 min. These changes were less than 0.03 mm, except for the first 30 min monitored.

Figure 4 shows the cumulative window deformation changes after monitoring for the first time. For 12 h after the phantoms were filled, the changes in the window deformations were up to 0.23 mm (for the PTW 41023#2), but were typically less than 0.16 mm.

Discussion

This work resulted in three findings. First, the six phantoms' entrance windows deformed as soon as the phantoms were filled. Next, after the phantoms were filled, the levels of window deformations gradually increased until the 12th hour, except for when monitored for the first time. Finally, the window deformations depended on the phantom types, phantom-to-phantom of the same type, time elapsed after the phantoms were filled, and the room temperature in the storage location.

Chamber depth in the phantoms investigated

As noted above, the windows deformed immediately after the six phantoms were filled. These results are in agreement with the window deformation behavior reported in IAEA TRS-398. Additionally, this work found that the window deformation changes for the first 30 min monitored were somewhat steep in comparison with those after the first 30 min (see Fig. 3). These findings suggest that the SSD could be determined more accurately if an operator carries out SSD settings after the first 30 min.

Assuming that ionization chamber measurements started approximately 1 h after the phantoms were filled because of the measurement setup and pre-irradiation of the ionization chamber, the chamber depth at the beginning of the measurements was generally 0.10–0.36 mm deeper than the desired depth, due to the window deformations, except for WP-34 #2 (see Fig. 2). These differences were within 0.5–1 mm of the positioning uncertainty mentioned in the TG-51 addendum[5] and by Muir et al[6]. Therefore, the window deformation would have a small effect on range measurements in proton and heavy ion therapy, and the determination of the depth of 50% of maximum ionization for electron beams.

After 1 h (when the measurements were assumed to begin), the change in the window deformations were less than 0.03 mm per 30 min (see Fig. 3); namely, the change in the chamber depth may be less than 0.03 mm for 30 min. Assuming that the probability distributions for the chamber depth are rectangular distributions within 0.03 mm, the associated uncertainty in the chamber depth (B-type) may be less than 0.01 mm (k=1) at most, when measurements are repeated at the same depth for 30 min. This uncertainty would not contribute significantly to the overall positioning uncertainty (e.g. 0.33 mm quoted from the TG-51 addendum[5]), because that is extremely smaller than the overall positioning uncertainty.

As can be seen in Figs. 2 and 4, the entrance windows gradually bow outward until 12 h after the measurements have started (1 h). However, these deformation changes were generally less than 0.1 mm; namely, the changes in the chamber depth in the phantoms would be generally less than 0.1 mm owing to the outward bowing during the measurements, which is not considered a significant change.

The behaviors of the window deformations were dependent on the room temperature conditions in the storage location, as shown in Fig. 2. These behaviors suggest that the chamber depth in the phantoms may vary on a daily basis when the phantoms are stored at varying room temperatures. Therefore, the phantoms may preferably be stored at roughly the same room temperature to eliminate the possibility of inadvertent errors in the chamber depth.

After the six phantoms investigated here were filled, the phantoms and the treatment table could tilt due to the weight of the phantoms with water. The authors believe that the table tilt should not affect the window deformation measurements because the dial indicator was placed on the table with the phantoms.

Influence of window deformation on dose measurement in various beam modalities

Generally, the phantoms investigated here are designed for reference dosimetry. Therefore, we discuss the influence of window bending on reference dosimetry in various beam modalities as follows.

Photon beams

Presuming that dose gradients at the calibration depth are approximately 2–4% per cm for 4–25 MV beams, the chamber depth changes (0.10–0.36 mm, as assumed above) at the beginning of the measurements translate to an error of 0.02–

0.07% at 25 MV, and 0.04–0.14% error at 4 MV in the dose calibrations. During measurements (for 11 h after the beginning of the measurements, as assumed above), the chamber depth change (0.1 mm, as mentioned above) due to the window deformation translates to an error of 0.02–0.04% in the chamber readings. Taken together, these results suggest that the change in the outward deformation, such as the humidity effect in clinical reference dosimetry,[7] can be ignored in beam calibration, and the determination of the ion recombination correction factor and polarity correction factor.

Electron beams

Assuming that the dose gradient at the calibration depth is approximately 0.02% per mm for the 6-MeV beam, the chamber depth change (0.10–0.36 mm, as assumed above) at the beginning of the measurements leads to an error of less than 0.01% in the dose calibration for 6 MeV and above, because the dose gradient for above 6 MeV is gentle in comparison with that for 6 MeV. Therefore, we suggest that the change in chamber depth due to the window deformation would be ignored in beam calibration.

Dose calibrations and the determination of the ion-recombination correction factor and polarity correction factor could take a couple of hours. The chamber depth change for this duration was less than or equal to approximately 0.05 mm at the most (see Fig. 4). The chamber depth change of 0.05 mm translates to an error of less than 0.01% for 6 MeV and above in the chamber readings, which indicate that the effect on the chamber depth would be insignificant during those measurements.

Light ion beams

For light ion beams, the calibration depth is the center of the spread-out Bragg peak (SOBP) or shallow (plateau region).[8] Change in the chamber depth due to the window deformation would not lead to a significant error in proton beam calibration. In comparison with the proton beam, an SOBP for heavy-ion beams is not flat, especially a narrow SOBP.[2] For example, the dose gradient in the SOBP for the carbon beam of 290 MeV/u with an SOBP width of 20 mm is approximately 1% per mm,[2] which indicates that the chamber depth changes of 0.10–0.36 mm (at the beginning of the measurements, as mentioned above) lead to an error of approximately 0.1–0.36% at the calibration depth. When a user measures with a phantom for horizontal beam delivery more accurately, these findings suggest that the operator shifts the chamber position at the beginning of the measurements from the actual depth to the desired depth (using window deformation data measured in the radiotherapy facility), especially heavy ion beams with a narrow SOBP.

Assuming that dose calibrations and determination of the ion recombination correction factor and polarity correction factor could take a couple of hours, chamber depth change for this duration is less than or equal to 0.05 mm at the most, as well as the electron beam. The chamber depth change (0.05 mm) would have a negligible effect on chamber reading for proton beams, and cause a level error of 0.05% in the chamber reading (1% per mm at the dose gradient, mentioned above) for the heavy ion beam. Therefore, the effect of these changes in the outward deformation on the dose calibrations and determination of the polarity correction factor would be negligible. With respect to the determination of the ion-recombination correction factor, if the commonly used method, as proposed by Weinhous and Meli[9], is used, the ratio of chamber readings is applied in a way that might amplify any small differences. Besides, since the ion-recombination correction factor is not measured during each occasion, the impact on this measurement might have an effect for a relatively extended period of time.

Conclusions

We discussed the influence of window deformation on the chamber depth and measurement in various beam modalities. For 30 min after the phantoms were filled, changes in the window deformation were somewhat steep in comparison with those after the first 30 min monitored. We recommend that an operator should avoid setting SSD for at least 30 min after a phantom is filled.

At the beginning of the measurement, the chamber depth was generally 0.10–0.36 mm deeper than the reference depth due to the window bending, assuming that the measurement was started 1 h after the phantoms were filled. The variations depended on model to model, even from phantom to phantom of the same model, and temperature of the storage room. These changes in the chamber depth would not influence the calibration of the photon, electron, and proton beams. When the reference depth for heavy-ion beams is the center of the SOBP, the dose gradient at the reference depth is not flat, which causes an error in the chamber reading due to the window bowing, for example, approximately 0.1–0.36% error assuming that the dose gradient is 1% per mm. These consequences for heavy-ion beams suggest that a user might shift a chamber in a phantom from the actual depth to the reference depth.

After the measurements were started, changes in the chamber depth due to the window deformation would be 0.05 mm at most for every couple of hours; the effect on reference dosimetry for various beam modalities should be small, except for determination of ion recombination correction factor for heavy ion beams. With respect to determination of ion recombination correction factor for the heavy ion beams, if the commonly used method as proposed by Weinhous and Meli is used, the ratio of chamber readings is applied in a way that might enlarge any small differences. In addition, since ion recombination correction factor are not measured during each occasion, the impact on this measurement might have an effect for a relatively extended period of time.

As mentioned above, the outward bowing of the phantom window deformation changed with the temperature of the storage room, which apparently indicates that the chamber depth may vary day by day when the phantoms are stored at varying room temperatures. Therefore, phantoms may preferably be stored at roughly the same room temperature.

Acknowledgments

The authors are grateful to Kenichi Ito of Tochigi Cancer Center, Kamada Shigeyoshi of Gifu Prefectural Tajimi Hospital, Hitoshi Sekino of QualitA, Mamoru Ishii of Euro Meditech, and Yoshinari Sakamoto of Toyo Meditech for lending the phantoms. The authors thank Takahiro Kato of the Southern Tohoku Proton Therapy Center, Hidenobu Tachibana of the National Cancer Center, and Kenji Hotta of the National Cancer Center for useful discussions on measurements in light ion beams. The study did not receive any financial support.

Disclosure of Conflicts of Interest: The authors have no conflicts to disclose.

References

1. McEwen MR, Kawrakow I, Ross CK. The effective point of measurement of ionization chambers and the build-up anomaly in MV x-ray beams. *Med Phys*. 2008;35(3):950-958.
2. Andreo P, Burns DT, Hohlfeld K, et al. *Absorbed Dose Determination in External Beam Radiotherapy: an International Code of Practice for Dosimetry based on Standards of Absorbed Dose to Water*. Vienna, Austria: IAEA Technical Report Series No. 398; 2000.
3. Arib M, Medjadj T, Boudouma Y. Study of the influence of phantom material and size on the calibration of ionization chambers in terms of absorbed dose to water. *J Appl Clin Med Phys*. 2006;7(3):55-64.
4. Kinoshita N, Oguchi H, Adachi T, Shioura H, Kimura H. Uncertainty in positioning ion chamber at reference depth for various water phantoms. *Rep Pract Oncol Radiother*. Rep Pract Oncol Radiother. 2018;23(3):199-206.
5. McEwen M, DeWerd L, Ibbott G, et al. Addendum to the AAPM's TG-51 protocol for clinical reference dosimetry of high-energy photon beams. *Med Phys*.

2014;41(4):041501.

6. Muir B, Culberson W, Davis S, et al. Insight gained from responses to surveys on reference dosimetry practices. J App Clin Med Phys. 2017;18:182–190.

7. Rogers DWO, Ross CK. The role of humidity and other correction factors in the AAPM TG-21 dosimetry protocol. *Med Phys*. 1988;15(1):40-48.

8. Palmans H, Vatnitsky SM. Beam monitor calibration in scanned light- ion beams. Med Phys. 2016;43(11):5835.

9. Weinhous MS, Meli JA. Determining P_{ion}, the correction factor for recombination losses in an ionization chamber. Med Phys. 1984;11(6):846-849.

Figure legends

Fig. 1. Experimental setup for the evaluation of the outward bowing behavior.

Fig. 2. Window deformation behaviors immediately after the six phantoms were filled. The error bars reflect variations expressed as the spread between minimum and maximum values in their deformation over several days.

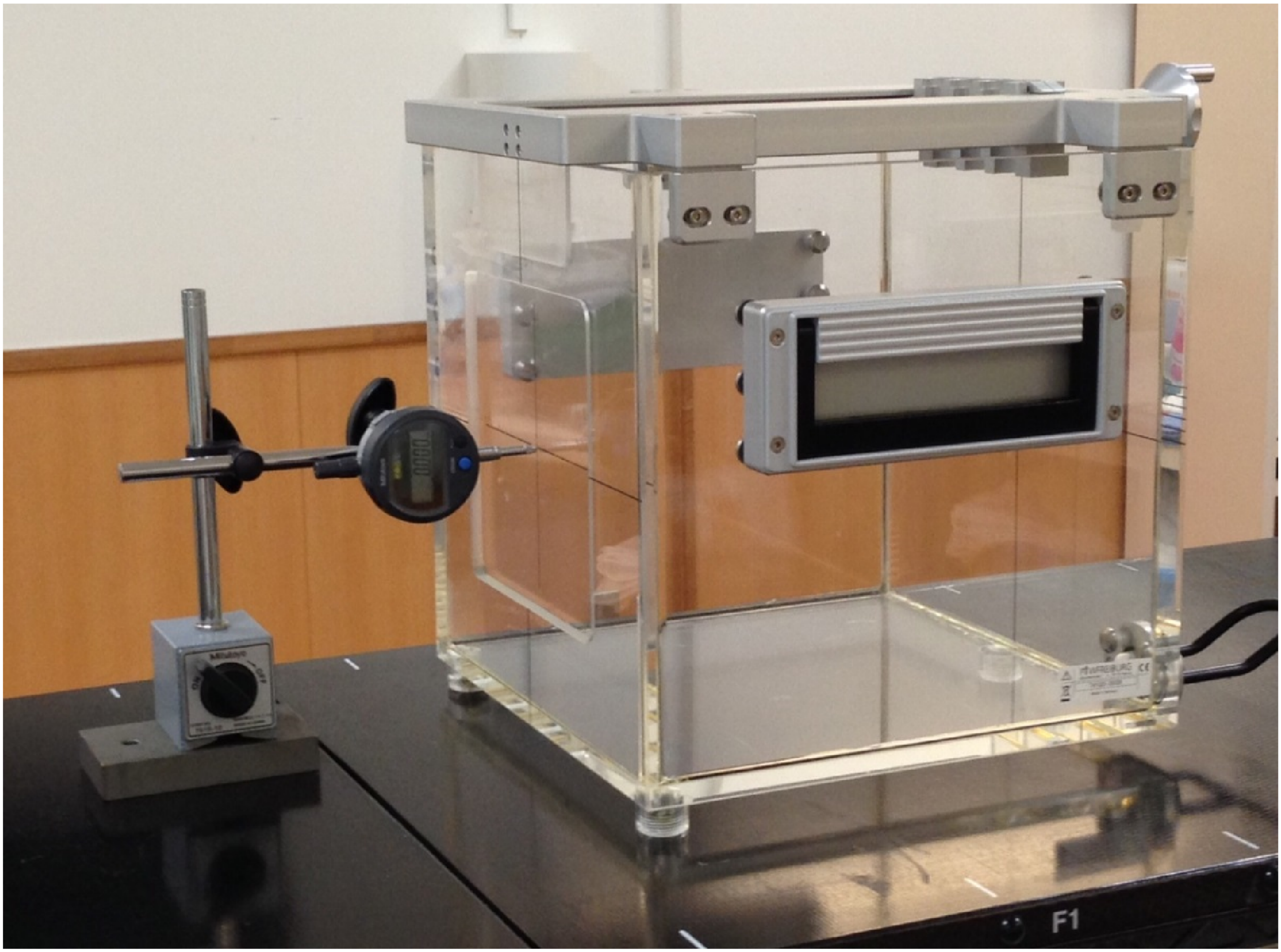
Fig. 3. Window deformation changes per 30 min. The error bars reflect variations expressed as the spread between minimum and maximum values in their changes over several days.

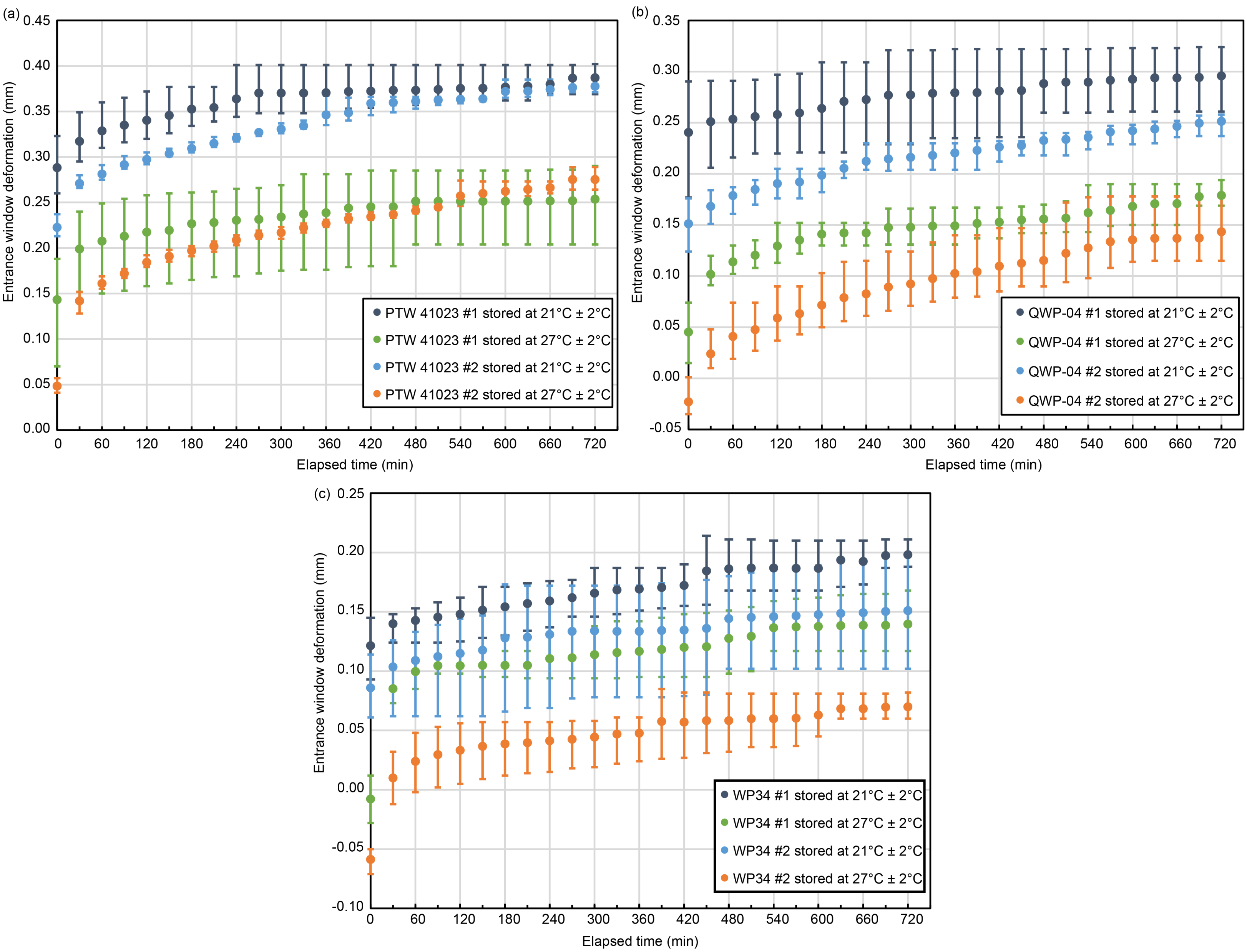
Fig. 4. Cumulative window deformation changes after monitoring for the first time. The error bars reflect variations expressed as the spread between minimum and maximum values in their changes after the first time, monitored over several days.

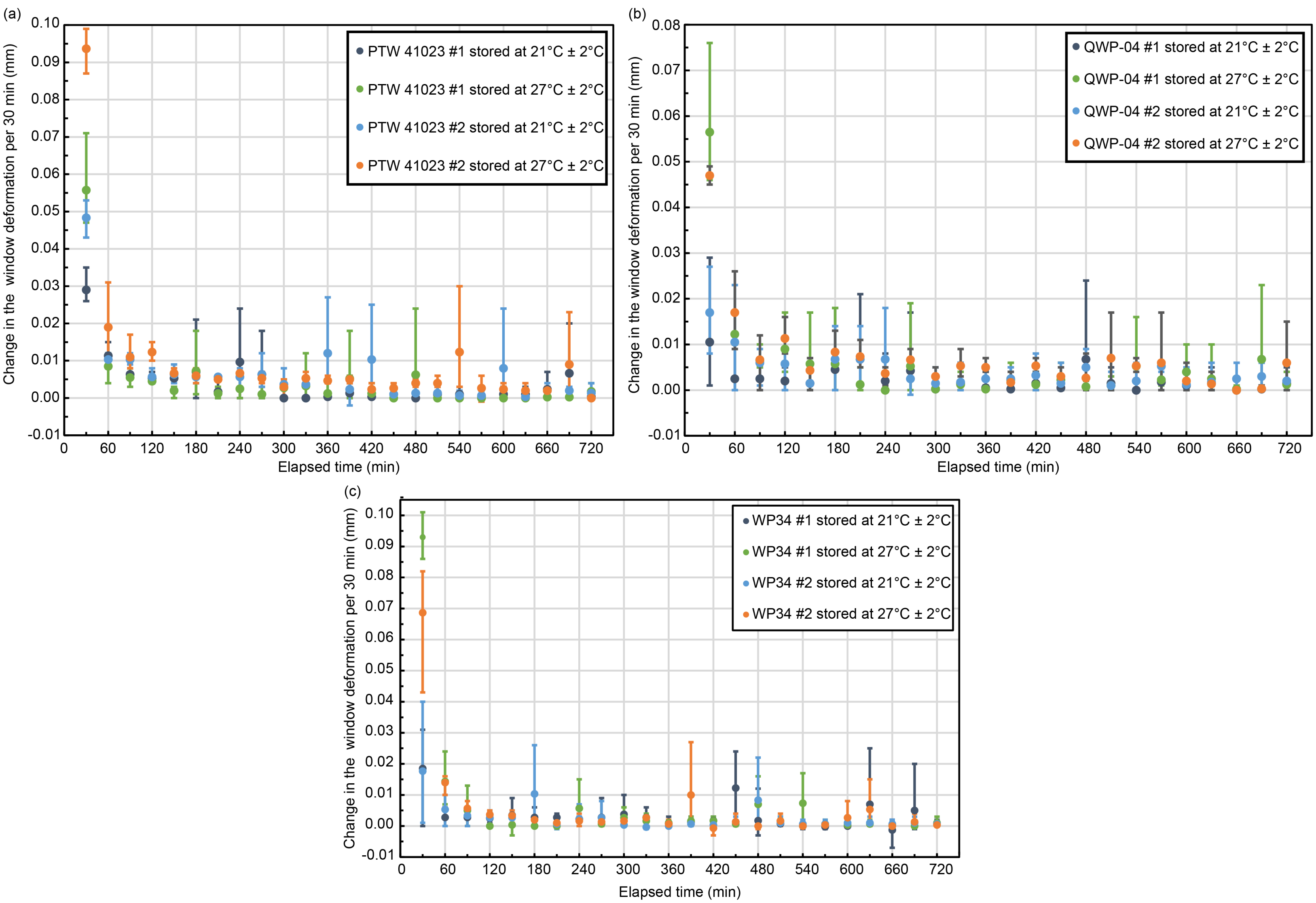
Table 1. Characteristics of the phantoms investigated

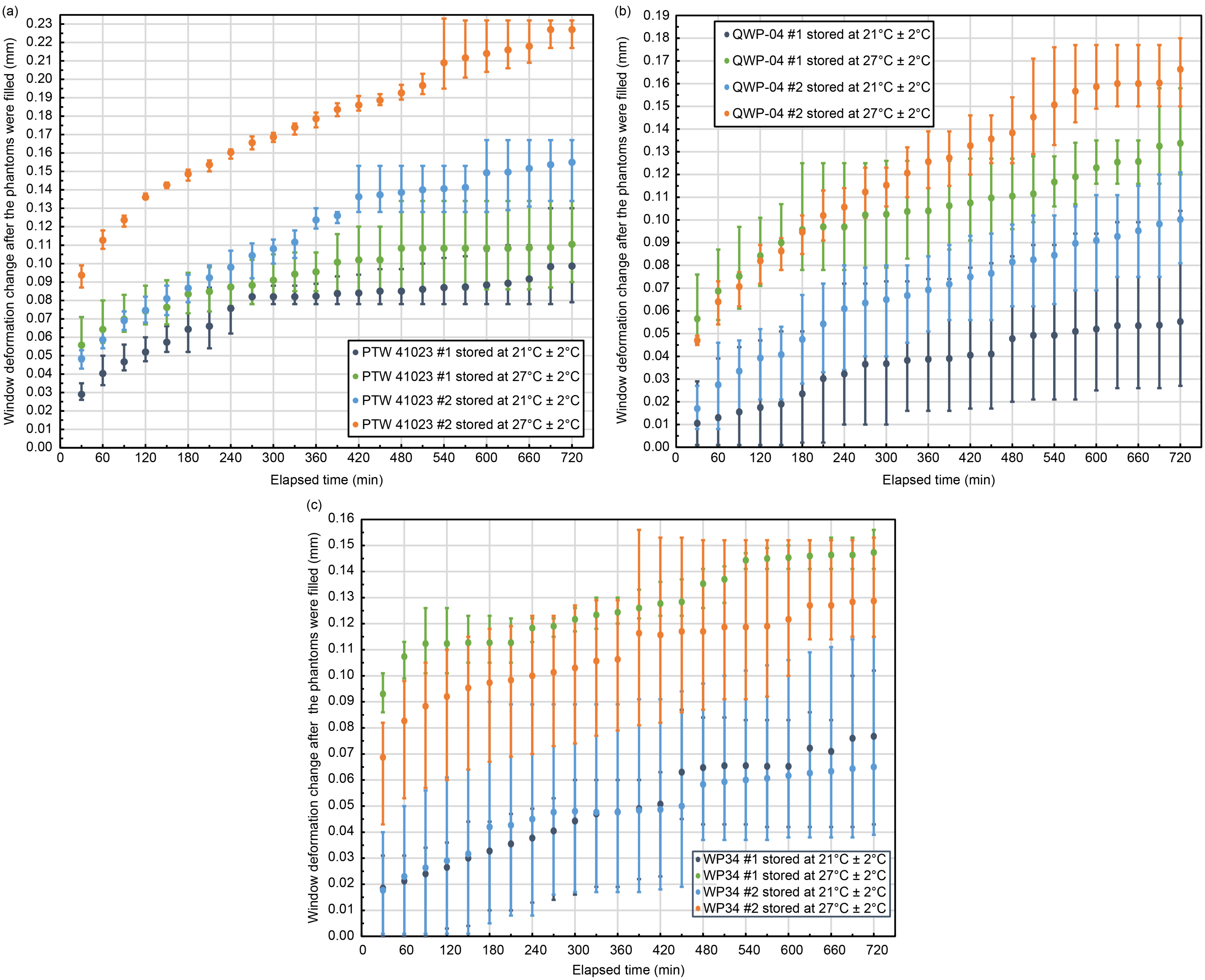
Phantom type	*Wall material*	*Size (inner)* $L \times W \times H$ *(cm^3)*	*Window Size (cm^2)*	*Window Thickness (mm)*
PTW 41023	PMMA[a]	28 × 28 × 29	17 × 17	3.05
QWP 04	PMMA	30 × 35 × 32	17 × 17	3
WP 34	PMMA	30 × 30 × 30	15 × 15	4

[a]PMMA: polymethylmethacrylate


F1


(a)
Entrance window deformation (mm)
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0
60
120
180
240
300
360
420
480
540
600
660
720
Elapsed time (min)
PTW 41023 #1 stored at 21°C ± 2°C
PTW 41023 #1 stored at 27°C ± 2°C
PTW 41023 #2 stored at 21°C ± 2°C
PTW 41023 #2 stored at 27°C ± 2°C
(b)
Entrance window deformation (mm)
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
-0.05
0
60
120
180
240
300
360
420
480
540
600
660
720
Elapsed time (min)
QWP-04 #1 stored at 21°C ± 2°C
QWP-04 #1 stored at 27°C ± 2°C
QWP-04 #2 stored at 21°C ± 2°C
QWP-04 #2 stored at 27°C ± 2°C
(c)
Entrance window deformation (mm)
0.25
0.20
0.15
0.10
0.05
0.00
-0.05
-0.10
0
60
120
180
240
300
360
420
480
540
600
660
720
Elapsed time (min)
WP34 #1 stored at 21°C ± 2°C
WP34 #1 stored at 27°C ± 2°C
WP34 #2 stored at 21°C ± 2°C
WP34 #2 stored at 27°C ± 2°C


(a)
PTW 41023 #1 stored at 21°C ± 2°C
PTW 41023 #1 stored at 27°C ± 2°C
PTW 41023 #2 stored at 21°C ± 2°C
PTW 41023 #2 stored at 27°C ± 2°C
Change in the window deformation per 30 min (mm)
Elapsed time (min)
(b)
QWP-04 #1 stored at 21°C ± 2°C
QWP-04 #1 stored at 27°C ± 2°C
QWP-04 #2 stored at 21°C ± 2°C
QWP-04 #2 stored at 27°C ± 2°C
Change in the window deformation per 30 min (mm)
Elapsed time (min)
(c)
WP34 #1 stored at 21°C ± 2°C
WP34 #1 stored at 27°C ± 2°C
WP34 #2 stored at 21°C ± 2°C
WP34 #2 stored at 27°C ± 2°C
Change in the window deformation per 30 min (mm)
Elapsed time (min)


(a)
Window deformation change after the phantoms were filled (mm)
Elapsed time (min)
PTW 41023 #1 stored at 21°C ± 2°C
PTW 41023 #1 stored at 27°C ± 2°C
PTW 41023 #2 stored at 21°C ± 2°C
PTW 41023 #2 stored at 27°C ± 2°C
(b)
Window deformation change after the phantoms were filled (mm)
Elapsed time (min)
QWP-04 #1 stored at 21°C ± 2°C
QWP-04 #1 stored at 27°C ± 2°C
QWP-04 #2 stored at 21°C ± 2°C
QWP-04 #2 stored at 27°C ± 2°C
(c)
Window deformation change after the phantoms were filled (mm)
Elapsed time (min)
WP34 #1 stored at 21°C ± 2°C
WP34 #1 stored at 27°C ± 2°C
WP34 #2 stored at 21°C ± 2°C
WP34 #2 stored at 27°C ± 2°C