Custom Phantoms for MRI Geometric Accuracy Quantification using CT-Based Image Matching in Brain Stereotactic Radiosurgery

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MEDICAL PHYSICS COMMUNITY · INSPIRATION · INNOVATION · IMPACT
2026 JULY 19–22 VANCOUVER, BC
JOINT AAPM | COMP MEETING

ABSTRACT

Purpose: Stereotactic radiosurgery (SRS) requires submillimeter geometric accuracy and commonly relies on computed tomography (CT) and magnetic resonance imaging (MRI) image fusion for precise target delineation. However, MRI is susceptible to geometric distortions that increase with distance from the scanner isocenter, potentially compromising target localization and treatment accuracy. This study presents the development and evaluation of cost-effective, in-house phantoms for quantifying MRI geometric distortions in brain SRS applications.

Methods: Three cylindrical phantom prototypes were developed: a LEGO-based phantom, a CNC-machined acrylic phantom, and a 3D-printed PETG lattice phantom. MR-compatible materials were evaluated based on moldability into wells, low CT density, and high MRI signal intensity. The LEGO and CNC-machined phantoms were filled with gelatin as the contrast medium, while the 3D-printed phantom used a copper sulfate solution. Phantoms were scanned using clinical brain SRS CT and MRI protocols, and geometric distortions were quantified using the Siemens Frontier Distortion Analysis Tool.

Results: Gelatin demonstrated suitable long-term stability, moldability, and imaging characteristics for use as an MR-compatible medium. The LEGO and CNC-machined phantoms produced visible grid structures on MRI. The CNC-machined phantom demonstrated a maximum geometric distortion of 1.39 ± 0.36 mm. Distortion analysis of the LEGO phantom was unreliable, resulting in an apparent maximum distortion of 9.98 ± 2.27 mm. The 3D-printed phantom is currently under construction.

Conclusion: Cost-effective in-house phantoms were successfully developed for MRI geometric distortion assessment in SRS. The CNC-machined phantom demonstrated relation distortion measurements, while further evaluation is required for the LEGO and 3D-printed approaches.

INTRODUCTION

Stereotactic radiosurgery (SRS) requires submillimeter geometric accuracy and relies on the integration of computed tomography (CT) and magnetic resonance imaging (MRI) for precise target delineation. However, MRI is inherently susceptible to geometric distortions caused by magnetic field inhomogeneities, gradient nonlinearities, and susceptibility effects, resulting in spatial misregistration between reconstructed and true anatomical locations. These distortions increase with distance from the scanner isocenter and can compromise target localization and overall treatment accuracy.

Commercially available distortion phantoms are often costly and may not be accessible to all clinical centers, particularly smaller or resource-limited facilities. Therefore, there is a need for affordable, in-house solutions that enable reliable, site-specific MRI geometric validation.

This study presents the design, development, and evaluation of three cost-effective phantoms for quantifying MRI geometric distortions in brain SRS applications.

METHODS AND MATERIALS

Three cylindrical phantoms were developed: LEGO-based (19.2 cm height, 9.54 cm radius, 1456 grid points), CNC-machined acrylic (20 cm height, 10 cm radius, 590 grid points), and a 3D-printed PETG lattice (22 cm height, 22 cm radius, 869 grid points) (Figure 1).

MR-compatible materials were evaluated based on moldability, long-term stability, melting point, CT density, and MRI signal intensity. Tested materials included Versagel® gelatin (isopropyl palmitate/styrene block polymer), paraffin-mineral oil (PMO) mixtures (1:1 and 1:4), paraffin, and silicone rubber.

The LEGO and CNC-machined wells in the phantoms were both filled with gelatin as the MR contrast medium, while the 3D-printed phantom will be immersed in a container filled with 0.9 mM copper sulfate solution.

All phantoms were imaged using a GE Healthcare Optima CT scanner with a clinical brain SRS protocol and a 3T Siemens MAGNETOM Vida MRI scanner using an axial T_1-weighted MPRAGE sequence. MRI geometric distortions were quantified using the Frontier Distortion Analysis Tool (Siemens Healthineers).

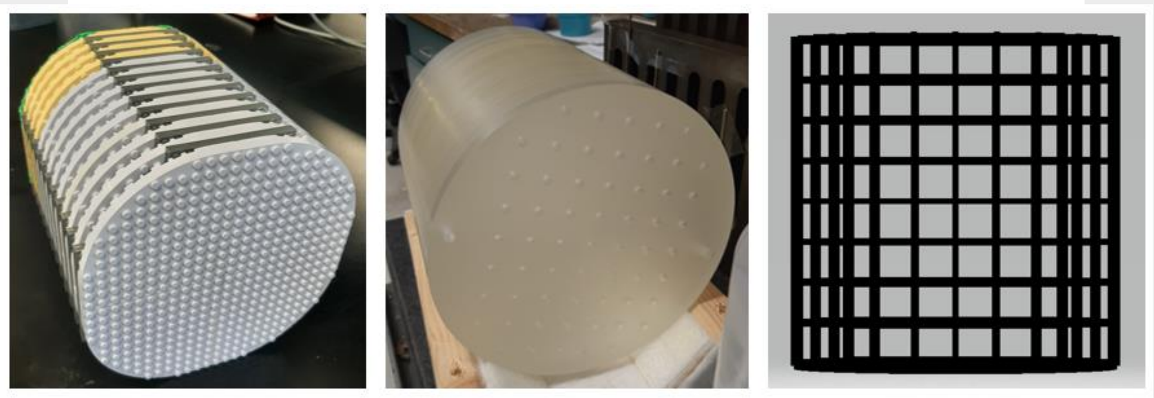

Figure 1. a) LEGO-based phantom, b) in-house CNC-machined acrylic phantom, and c) 3D-printed filament-based lattice phantom

RESULTS

All contrast materials demonstrated stable Hounsfield unit (HU) values and suitable moldability. However, gelatin exhibited superior long-term thermal stability and the highest HU values, making it most suitable for MRI (Figure 2).

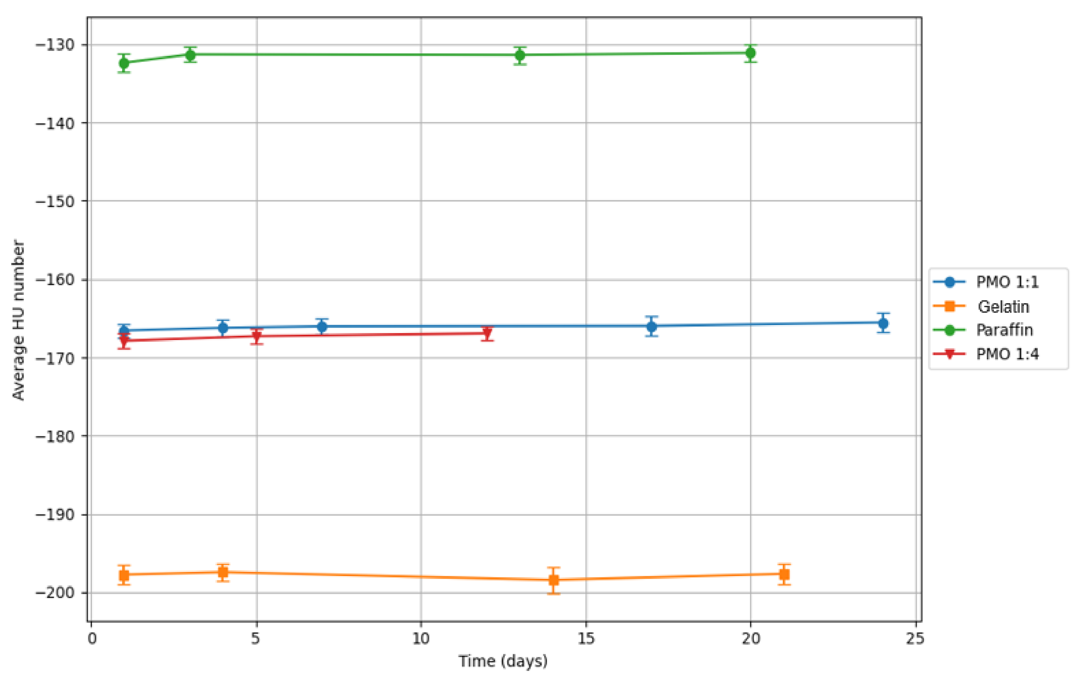

Figure 2. Stability of average Hounsfield Unit (HU) over time for paraffin-mineral oil 1:1 (PMO-1:1), PMO-1:4, gelatin, and paraffin.

CT and MR images of the LEGO and CNC-machined phantoms are shown in Figure 3. During MRI acquisition, the $MnCl_2$ signal generator was positioned directly on top of the phantom at its center, with the head flex coil placed directly over the setup. This configuration introduced image artifacts and increased the overall setup height, limiting visualization of grip points at the phantom base.

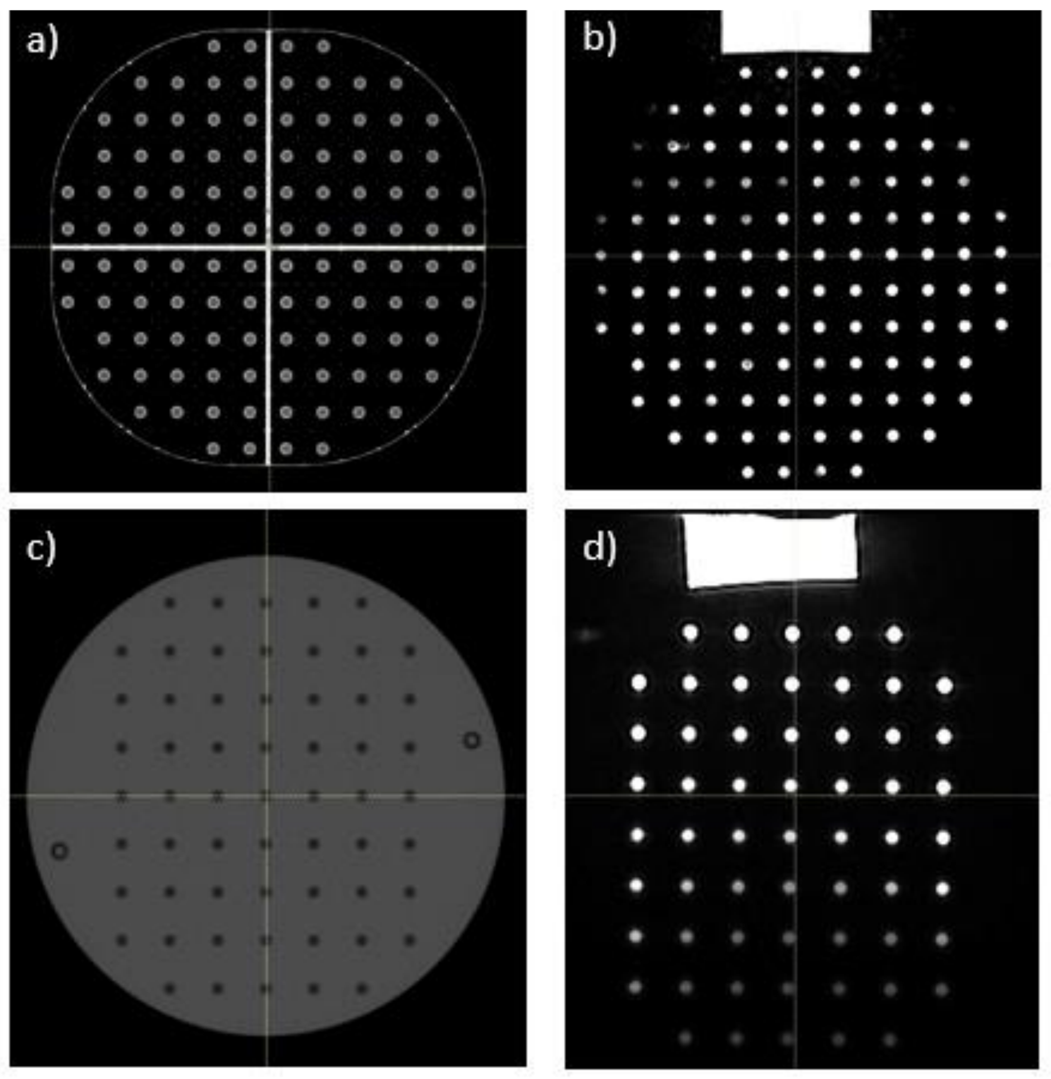

Figure 3. a) CT of LEGO phantom, b) MRI of LEGO phantom, c) CT of machined phantom, and d) MRI of machined phantom.

Geometric distortions were quantified using the Frontier Distortion Analysis tool (Figure 4). The maximum measured distortion was **1.39 ± 0.36 mm** for the CNC-machined phantom and **9.98 ± 2.27 mm** for the LEGO phantom. However, automated analysis of the LEGO phantom was unreliable due to interference from the glued intersections within the structure.

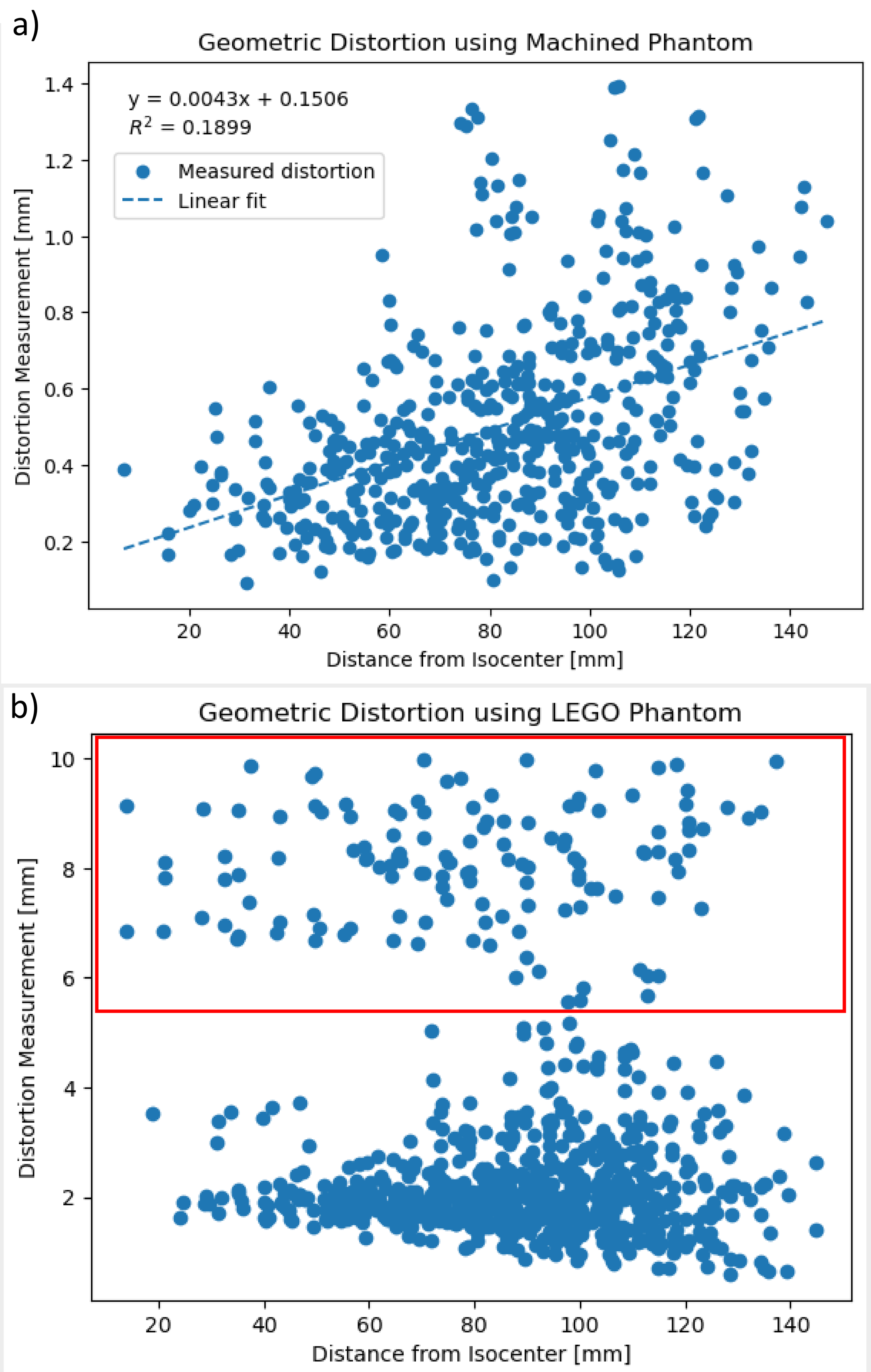

Figure 4. Geometric distortion measurement using a) machined phantom and b) LEGO phantom.

The red-boxed data points represent unreliable measurements, corresponding to the glued intersections between LEGO pieces. These features appear as the visible cross-shaped structures in Figure 3(a) and were incorrectly detected by the distortion analysis software. A more comprehensive analysis will be performed to further evaluate the data.

DISCUSSION & CONCLUSIONS

Key limitations:

- Signal generator placement increased setup height, limiting head coil coverage and visualization of the phantom base.
- Signal generator introduced image artifacts, slightly distorting the MR images.
- Glued LEGO intersections affected automated distortion analysis accuracy, resulting in incorrect feature detection and loss in reliable distortion measurements.
- 3D-printed phantom evaluation is ongoing.

To conclude, in-house cost-effective phantoms show promise for MRI geometric distortion assessment in SRS. The CNC-machined phantom provided reliable measurements, and gelatin was identified as a suitable MR-compatible medium. Future design improvements will enhance accuracy and clinical implementation.

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