Technical Note: Rapid prototyping of 3D grid arrays for image guided therapy quality assurance

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Three dimensional grid phantoms offer a number of advantages for measuring imaging related spatial inaccuracies for image guided surgery and radiotherapy. The authors examined the use of rapid prototyping technology for directly fabricating 3D grid phantoms from CAD drawings. We tested three different fabrication process materials, photopolymer jet with acrylic resin (PJ/AR), selective laser sintering with polyamide (SLS/P), and fused deposition modeling with acrylonitrile butadiene styrene (FDM/ABS). The test objects consisted of rectangular arrays of control points formed by the intersections of posts and struts (2 mm rectangular cross section) and spaced 8 mm apart in the x, y, and z directions. The PJ/AR phantom expanded after immersion in water which resulted in permanent warping of the structure. The surface of the FDM/ABS grid exhibited a regular pattern of depressions and ridges from the extrusion process. SLS/P showed the best combination of build accuracy, surface finish, and stability. Based on these findings, a grid phantom for assessing machine-dependent and frame-induced MR spatial distortions was fabricated to be used for quality assurance in stereotactic neurosurgical and radiotherapy procedures. The spatial uniformity of the SLS/P grid control point array was determined by CT imaging (0.6 × 0.6 × 0.625 mm³ resolution) and found suitable for the application, with over 97.5% of the control points located within 0.3 mm of the position specified in CAD drawing and none of the points off by more than 0.4 mm. Rapid prototyping is a flexible and cost effective alternative for development of customized grid phantoms for medical physics quality assurance. © 2008 American Association of Physicists in Medicine. [DOI: 10.1118/1.3006198]

Key words: imaging phantoms, stereotactic techniques, radiotherapy planning, 3D imaging

INTRODUCTION

Rapid prototyping refers to a family of automated processes for fabricating solid objects directly from a computer model without machining or tooling. We have explored the use of rapid prototyping to fabricate high density grid phantoms for assessing frame-related MR distortion in stereotactic neurosurgical/radiosurgical procedures. Heretofore, these grids have been assembled from stock pieces of commercially available 2D grids. However, producing uniformly spaced control points in 3D by conventional methods is problematic, and we turned to rapid prototyping as an alternative approach.

Three rapid prototyping processes were tested, each with a different build material. Based on our preliminary assessment, a polyamide grid phantom containing 2873 control points was fabricated using selective laser sintering process. The phantom was designed to be attached to the head ring of a Leksell stereotactic frame for assessing frame-induced MRI spatial distortions. The observed strengths and weaknesses of the three prototyping technologies are presented...
along with the results of acceptance testing of the grid phantom for frame-based neurosurgical procedures.

METHODS

Grid phantoms

The design for the cylindrical test grids was adapted from Wang et al. The grid was formed by the intersection of posts and struts (2 \times 2 \text{ mm}^2 \text{ rectangular cross section}) producing a rectangular array of control points spaced at 8 mm distance over the entire volume (Fig. 1). The final model was saved in stereolithography CAD format (STL, 3D Systems, Rock Hill, SC, USA) for electronic submission to the rapid prototyping service. Turnaround time from submission to shipment was 3 days or less.

The small grids (69.25 mm diameter \times 55 mm length with 384 control points) used for preliminary testing were constructed from the same specifications as detailed in Figs. 1(a)–1(d). Each of these test objects was fabricated with a different build material and each by a different service provider: (i) Polyjet with acrylic resin (PJ/AR), an ink-jet process in which a print head deposits a photopolymer powder (Verobluce) which is immediately cured to form the build layer; (ii) fused deposition modeling with acrylonitrile butadiene styrene (FDM/ABS), an extrusion process in which a filament of plastic material (ABS45101) is melted at the point of deposition by a heated extrusion nozzle and then hardens with cooling to form the build layer; and (iii) selective laser sintering with polyamide (SLS/P), a fusion process in which powdered material (DuraForm) is heated with an infrared laser to sinter the powder forming the build layer.

Larger grids (13.8 cm diameter \times 10.6 cm length with 2873 control points) were also fabricated for use in assessing MR imaging distortions caused by the Leksell stereotactic frame. Two process materials were examined, PJ/AR and SLS/P.

Imaging

Grids were imaged in a GE Medical Systems LightSpeed VCT at a resolution of 0.234 \times 0.234 \times 0.625 \text{ mm}^3 for the small grids and 0.596 \times 0.596 \times 0.625 \text{ mm}^3 for the large SLS/P grid Leksell frame assembly. The large PJ/AR grid was visibly warped as received from the supplier and was not scanned.

Grids were immersed in an aqueous salt solution (3.60 g NaCl and 1.955 g CuSO\textsubscript{4} \cdot 5H\textsubscript{2}O per liter dH\textsubscript{2}O). MRI was acquired using a 3D imaging sequence, MPRAGE, with TR =2000 ms and TE=2.07 ms, 1 \times 1 \times 1 \text{ mm} resolution (1.5 T Symphony, Siemens Medical Solutions, Erlangen, Germany).

The coordinates of the center of mass for the six grid posts forming each control point were determined after convolution of the image volume with a 3D cross using an automated method for identifying the local maxima. Measurements derived from these coordinates were compared to those derived using coordinates identified by the Prewitt operator first moment method described by Baldwin et al. No significant difference was detected between the two methods.

Measurements

The length and diameter of the test objects were measured with a caliper (accuracy: 0.05 mm) and compared to design specifications. Length measurements were taken at four different positions corresponding to 0°, 90°, 180°, and 270° along the perimeter of the cylindrical grid. Two width measurements were taken along the length of the structure at the seven positions indicated in Fig. 1(d).

CT imaging was used to assess the accuracy of the grid array since internal control points were not accessible for physical measurement. The distance between control points within the grid was calculated from the coordinates of the control points in the image volume. The accuracy for the CT measurements was assessed by comparing CT with caliper measurements. The accuracy of the CT measurements was generally found to be within the limits of accuracy of the caliper (0.05 mm).

In some of the grids, local deformations within the rectangular array or generalized warping were detected by visual inspection. Neither the caliper nor the CT measurements systematically characterized these local deformations. To quantify the overall geometric accuracy of the grid arrays (including the effect of local warping), the coordinate matrix of grid intersection points was translated and rotated to be aligned with the CAD matrix. This approach provides a measure of the spatial uniformity of the control point array within the 3D grid. The spherical coordinates of the error vector for...
RESULTS

Surface finish and warping

All of the prototyping processes tested employ a similar fabrication approach, depositing build material along a line and then raster scanning the fabrication head/build platform to complete the build layer. The 3D object is created by repeating this sequence, fusing the next build layer to the underlying material. The layering process is evident in Fig. 2 particularly in the surface detail of the rectangular posts.

The surface of the PJ/AR grid was the smoothest of all the processes. The surface finish of the SLS/P structure was more textured. The FDM/ABS grid had the least consistent finish, exhibiting a pattern of depressions and ridges along the surface of the build layer. A CT scan through the circular grid in the FDM/ABS test object showed a similar pattern of subsurface variability in deposition of the build material, presumably arising from the weave of the extrusion process (data not shown).

Each of the grid intersections were determined (directed distance from the CAD specified coordinate to the CT localized grid intersection).

Statistical analyses were performed using JMP version 7 (SAS Institute, Cary, NC, USA). Data are reported as means ± standard deviations. Statistical significance was assumed at a \( p < 0.05 \).

The FDM/ABS and PJ/AR grids were noticeably warped as received from the supplier. The deformation in the small FDM/ABS grid involved the grid disks near the middle of the object. The FDM/ABS grid bowed inwards perpendicular to the \( z \) axis. The large PJ/AR grid warp occurred along the \( z \) axis, with one end of the structure bowing outward and the opposite end bowing inward (Fig. 3). A similar pattern was observed in the small PJ/AR grid.

Caliper measurement of the test grids

The dimensional errors for all of the processes tested were small (summarized in Table I). For the SLS/P and PJ/AR grids, the differences between the measured and specified dimensions were generally within the accuracy of the caliper (\(<0.05\) mm for spans of 70 mm). For the FDM/ABS grid, the build errors were larger but still within a 1% tolerance range for the specified build dimension.

CT measurements of the grid control point arrays

The span distance between neighboring control points within the grid array was used as a second measure of build accuracy. The measured distances to the nearest neighboring control points in the \( x \), \( y \), and \( z \) directions for each build process is summarized in Table I. All of the process material tested produced acceptable accuracy in the spacing of the control points (generally within 1% tolerance range for the specified 8 mm spacing).

Stability after immersion in water

The PJ/AR grid continuously expanded after immersion in water, in particular, during the first week. By day 33, the diameter of the grid had increased nearly 2% over its dry dimension. The effect was partially reversed by drying the structure in air. The FDM/ABS grid showed no signs of expansion in water. The SLS/P grid showed a very slight expansion, less than 0.1%, evident within the first 6 days after

![Fig. 2. Photographs showing the surface finish of the small test grids. Top panels show the surface of the topmost grid disk, and the bottom panels show an enlargement of an individual post and the layering of the build material. Each pair (top and bottom) are from the same structure; the leftmost panels show the test object fabricated with PJ/AR, the middle panel with FDM/ABS, and the rightmost with SLS/P. The striations along the surface of the build layer in the PJ/AR test grid reflect the direction of the build line and the thin layering used in the PJ process. In comparison with the PJ/AR grid, the surface finish of the SLS/P structure had an almost fibrous look and feel. The FDM/ABS grid surface was uneven, marked by a regular pattern of ridges and depressions. Note the much thicker (200–300 \( \mu \)m) build layers in the FDM/ABS grid. The PJ process uses very thin (16 \( \mu \)m) layers that can be seen along the edges of the post.](image1)

![Fig. 3. Deformation/warping of the test grids. Top panel: Misalignment of the posts spanning grid disks 2–6 of the FDM/ABS test grid. The deformity was apparent as shipped from the service provider. Warping of the PJ/AR structure was seen in the small test object (not shown) and more prominently in the full size grid phantom shown in the bottom panels. Leftmost panel is a photograph looking along the top of the full size PJ/AR grid, and the rightmost panel shows an axial CT section through the center of the structure. Both panels reflect the warping of the grid along the central axis of the PJ/AR grid structure.](image2)
immersion. No further expansion was observed thereafter (for up to 6 months after immersion in copper sulfate solution used for MR imaging).

### Grid phantom for stereotactic frame-based neurosurgical and radiotherapy applications

The grid phantom assembly fabricated for assessing MR spatial distortion from a stereotactic head frame is shown in Fig. 4. The grid intersections were easily distinguished in both MR and CT images as were the localizer fiducials used to register the control points in stereotactic frame space. The spatial uniformity of the SLS/P grid control point array was determined by CT imaging (0.6 × 0.6 × 0.625 mm³ resolution) and found suitable for the application. Over 97.5% of the control points were within 0.3 mm of the CAD specified position and none of the points were off by more than 0.4 mm. The mean build error (Euclidean distance between the specified and observed positions) for the 2873 control points was 0.16 ± 0.06 mm.

DISCUSSION

Earlier work by Wang et al. and Baldwin et al. clearly demonstrated the utility of 3D grids for evaluating geometric distortion in imaging physics. Rapid prototyping will make it easier for physicists to access custom grids for specific applications. While the focus of our efforts has been neurosurgical/radiosurgical applications, SLS can print 3D objects up to 55 × 55 × 75 cm³. Thus, SLS would easily handle the dimensions of the grid phantoms constructed by Wang et al. (31 cm cube) and Baldwin et al. (30 cm cube) for use in assessing geometric distortion in a MR body coil. Based on our experience, the SLS/P process material would be recommended as a starting point for fabrication of larger grids for body imaging applications.

There are other rapid prototyping technologies, most having specifications for accuracy and feature detail suitable for use in fabricating imaging phantoms. We did not pursue stereolithography (SLA), even though this process was reported to offer the greatest accuracy and best surface finish of all the rapid prototyping techniques. The SLA process, like PJ, uses photopolymerization for building structures, and we were concerned that the SLA process would be subject to the same stability problems encountered in the PJ/AR grid. Other processes such as 3D printing which uses starches or plaster as the build material and laminated object manufacturing with paper were rejected for similar reasons.

The experiences reported here are based on interactions with a single service provider and at most two builds for each of the processes evaluated. Thus, the findings reported may not accurately reflect the properties of the build technologies. Nonetheless, the general lessons learned in developing the Leksell frame phantom described in this report are likely relevant to all applications. The selection of an appropriate technology/build material and a reliable commercial service are critical.

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**Table I. Mean absolute error (in mm) observed with rapid prototyping of the small test grids.**

<table>
<thead>
<tr>
<th>Process/build direction</th>
<th>Diameter/length (caliper)</th>
<th>Control point span (CT)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>X (N=7)</td>
<td>Y (N=7)</td>
</tr>
<tr>
<td>Laser sintering (SLS/P)</td>
<td>&lt;0.05</td>
<td>&lt;0.05</td>
</tr>
<tr>
<td></td>
<td>[0.02%]</td>
<td>[0.05%]</td>
</tr>
<tr>
<td>Photopolymer jet (PJ/AR)</td>
<td>&lt;0.05</td>
<td>0.25 ± 0.05</td>
</tr>
<tr>
<td></td>
<td>[0.07%]</td>
<td>[0.4%]</td>
</tr>
<tr>
<td>Fused deposition (FDM/ABS)</td>
<td>0.5 ± 0.3</td>
<td>0.6 ± 0.5</td>
</tr>
<tr>
<td></td>
<td>[0.8%]</td>
<td>[0.9%]</td>
</tr>
</tbody>
</table>

a Variance equivalence: Two-sided F test, significantly different from both other processes (p < 0.01).
b Mean difference test, t-test, significantly different from both other processes p < 0.01.

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**Fig. 4.** Photographs showing the full size SLS/P test phantom within the imaging chamber fixed to the head ring of a Leksell stereotactic frame. Left: Four white screws at the end of the imaging chamber cover the registration ports that permit access to verify the location of the grid in stereotactic frame space. Center: The localizer panels of the Leksell stereotactic frame system are installed. The location of the control points can be registered in stereotactic frame space using fiducials in the localizer panels. Right: CT (upper) and MR (lower) images of the SLS/P test phantom showing grid and the surrounding localizer panel and fiducials.
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