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Title: Patient-Specific Polyvinyl Alcohol Phantom Fabrication with Ultrasound and X-Ray Contrast for Brain Tumor Surgery Planning

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Author Questionnaire

1. Microscopy: Does your protocol involve video microscopy, such as filming a complex dissection or microinjection technique? **N**

2. Software: Does the part of your protocol being filmed demonstrate software usage? **Y**

If **Yes**, we will need you to record using screen recording software to capture the steps. If you use a Mac, QuickTime X also has the ability to record the steps. Please upload all screen captured video files to your project page as soon as possible.

3. Filming location: Will the filming need to take place in multiple locations (greater than walking distance)? **N**

Protocol Length

Number of shots: **54**

Introduction

1. Introductory Interview Statements

REQUIRED:

1.1. **Jonathan Shapey**: Phantoms models are important tools, but it is challenging to make them anatomically accurate. This protocol uses CT and ultrasound to create a patient-specific brain phantom that includes a tumour **[1]**.

1.1.1. INTERVIEW: Named talent says the statement above in an interview-style shot, looking slightly off-camera

REQUIRED:

1.2. **Eleanor Mackle**: We use complex, heterogeneous models and 3D printing to achieve a high degree of anatomical realism **[1]**.

1.2.1. INTERVIEW: Named talent says the statement above in an interview-style shot, looking slightly off-camera

OPTIONAL:

1.3. **Jonathan Shapey**: Patient-specific brain phantoms are highly useful for surgical planning and clinical training, as they allow surgeons to practice new techniques and to test new instruments and hardware **[1]**.

1.3.1. INTERVIEW: Named talent says the statement above in an interview-style shot, looking slightly off-camera

Protocol

2. 3D Brain, Tumor, and Skull Mold Creation

2.1. After obtaining pre-operative contrast-enhanced T1-weighted MRI (M-R-I) and volumetric CT (C-T) data, load the images into a 3D modeling software program **[1-TXT]** and use the **Plane cut** tool to split the **Brain** segmentation into two hemispheres **[2]**.

2.1.1. WIDE: Talent loading images onto computer, with monitor visible in frame **TEXT: MRI: magnetic resonance imaging; CT: computed tomography**

2.1.2. SCREEN: screenshot1: 00:30-01:20 *Video Editor: please speed up*

2.2. Save each hemisphere as separate right and left brain STL files **[1]** and import the files into an appropriate computer-aided design software program **[2]**.

2.2.1. SCREEN: screenshot1: 01:28-01:40

2.2.2. Talent importing file into program, with monitor visible in frame

2.3. In the mesh workspace, use the **Reduce** function to decrease the size of each model as much as possible so that it can be handled by the program while still retaining all of the necessary detail **[1]**.

2.3.1. SCREEN: screenshot2: 00:16-00:30

2.4. In the solid workspace, use the **Mesh to BRep** (B-rep) tool to convert the imported mesh to a body that can be manipulated **[1-TXT]**.

2.4.1. SCREEN: screenshot2: 00:34-00:44 **TEXT: Further reduce mesh as necessary**

2.5. Click **Create** and **Box** to draw a box around the tumor, rotating the view to ensure that the box completely encloses the tumor on all sides **[1]**.

2.5.1. SCREEN: screenshot3: 00:05-00:36 *Video Editor: please speed up*

2.6. In the **Operation** dropdown menu, designate the box as a **New Body [1]**.

2.6.1. SCREEN: screenshot3: 00:48-00:55

2.7. Click the **Modify** tab and use the **Combine** tool to cut the tumor from the box to create a box with a hollow shape of the tumor inside of it **[1]**.

2.7.1. SCREEN: screenshot4: 00:16-00:38 *Video Editor: please speed up*

2.8. To create planes through the box in the places that the mold will be cut, click **Construct** and **Midplane** to create a plane through the center of the box **[1]**.

2.8.1. SCREEN: screenshot5: 00:14-00:36

2.9. Right click on the midplane and select **Offset Plane** to position the plane more precisely **[1]**.

2.9.1. SCREEN: screenshot5: 01:10-01:28

2.10. Under the **Modify** tab, use the **Split Body** function to split the mold along the created planes **[1]** and click **Create sketch** and **Centre diameter circle** to add small, circular rivets to the face of each piece of the mold **[2]**.

2.10.1. SCREEN: screenshot6: 00:09-00:33 *Video Editor: please speed up*

2.10.2. SCREEN: screenshot6: 00:53-01:23 *Video Editor: please speed up*

2.11. Right click to **Extrude** the circles outward a few millimeters on one face and extrude them inward on the corresponding face **[1]**.

2.11.1. SCREEN: screenshot7: 00:39-01:06

2.12. Then save each piece of the mold as a separate STL file **[1]**.

2.12.1. SCREEN: screenshot8: 00:18-00:30

3. 3D Printing

3.1. To print the 3D brain and tumor molds, for faster printing, select a large layer height of about 0.2 millimeter **[1]** and a low infill value of about 20% in the 3D printing software. If the moulds are positioned appropriately on the base plate, support material should not be necessary **[2]**.

3.1.1. WIDE: Talent selecting layer height, with monitor visible in frame

3.1.2. SCREEN: To be provided by Authors: Infill value being selected NOTE: This and 3.3.1 not uploaded at the time of postshoot processing, author was reminded.

3.2. Print the molds using a rigid material such as polylactic acid **[1]**. ~~[2].~~

3.2.1. Mold being printed

~~3.2.2. Mold(s) being positioned~~

3.3. Before printing the skull mold, select **Add support** in the software to use PVA (P-V-A) as the support material **[1-TXT]**.

3.3.1. SCREEN: To be provided by Authors: Add support being selected **TEXT: PVA: polyvinyl alcohol**

4. PVA Preparation

4.1. To prepare the PVA for the models, heat 1800 grams of deionized water to 90 degrees Celsius in a 2-liter conical flask **[1]** and measure out 200 grams of PVA powder **[2]**.

4.1.1. WIDE: Talen t placing flaks at 90 °C

4.1.2. Talent adding PVA to weight boat on balance

4.2. Position an electronic stirrer in the flask, taking care that it does not touch the bottom or sides **[1]** and set the speed to 1500 revolutions per minute **[2]**.

4.2.1. Stirrer being positioned

4.2.2. Talent setting rpm

4.3. Add the PVA powder to the flask over a period of about 30 minutes **[1]**.

4.3.1. Talent adding PVA to flask

4.4. When all of the PVA has been added, stir the solution for an additional 90 minutes **[1]**.

4.4.1. Solution being stirred

4.5. When a sticky gel has been obtained, remove the flask from the water bath **[1]** and cover the top with plastic wrap to prevent the formation of a skin on top of the material **[2]**.

4.5.1. Talent removing flask

4.5.2. Talent covering flask

4.6. Once cooled, the PVA will appear transparent **[1]**. Pour it into a beaker. Tiny white crystals may be observed, but any bubbles on the surface must be gently scraped off **[2]**.

4.6.1. Shot of transparent PVA *Videographer: Important step*

4.6.2. ECU: Shot of crystals, then bubbles being scraped Author NOTE: No crystals were visible in the batch made for filming, so there is no shot of the crystals here, only the bubbles being scraped off. *Videographer: Important step*

4.7. Then add 0.5% potassium sorbate to the PVA as a preservative **[1]** and thoroughly stir the solution **[2]**.

4.7.1. Talent adding potassium sorbate to flask, with potassium sorbate container visible in frame

4.7.2. Talent stirring solution

5. Phantom Preparation and Assembly

5.1. To prepare the phantoms, measure out enough PVA to fill the tumor mold into a beaker **[1]** and pour the rest into a separate beaker **[2]**.

5.1.1. WIDE: Talent measuring PVA NOTE: Videographer's log for this step reads "Board not incremented, shot terminated".

5.1.2. Talent pouring PVA into beaker

5.2. To prepare the PVA for the tumor, add 1% glass microspheres for ultrasound contrast **[1]** and 5% barium sulfate for X-ray contrast to the first beaker **[2]** and stir the resulting solution by hand **[3]**.

5.2.1. Talent adding microspheres to beaker, with microspheres container visible in frame

5.2.2. Talent adding barium sulfate to beaker, with barium sulfate container visible in frame

5.2.3. Talent stirring solution

5.3. Sonicate the beaker to ensure homogenous mixing of the additives **[1]** and allow the solution to cool for about 10 minutes **[2]**, removing any bubbles by scraping as necessary **[3]**.

5.3.1. Talent sonicating beaker

5.3.2. Talent placing beaker onto bench

5.3.3. Bubble(s) being removed

5.4. Secure the tumor mold together **[1]** and pour the PVA through the hole in the top of the mold **[2]**.

5.4.1. Mold being taped

5.4.2. Talent pouring PVA into mold NOTE: combined with 5.4.1.

5.5. Allow the PVA to rest for a few minutes to allow any bubbles formed in the pouring process to escape through the hole **[1]** before placing the mold into a minus 20-degree Celsius freezer **[2]**.

5.5.1. Talent setting timer, with mold visible in frame

5.5.2. Talent placing mold into freezer

5.6. After 6 hours, thaw the mold for 6 hours at room temperature **[1]**.

5.6.1. Talent placing mold onto bench

5.7. Repeat the 12-hour freeze-thaw cycle, then carefully remove the mold from the model **[1]**.

5.7.1. Mold being removed

5.8. Create the cerebellum and brain hemisphere models in the appropriate molds as just demonstrated **[1]**.

5.8.1. Tumor being placed into mold *Videographer: Important step*

5.8.2. Talent pouring PVA into mold *Videographer: Important step*

5.9. After the second freeze-thaw cycle for each phantom model piece, carefully remove the models from the molds and place the cerebellum tumor phantom on the spike at the base of the skull bottom model **[1]**.

5.9.1. Mold(s) being removed *Videographer: Important step*

5.9.2. ~~Talent placing cerebellum tumor phantom onto spike~~ *Videographer: Important step*

5.10. Place the two brain hemispheres into the uppermost part of the Cerebellum tumor piece **[1]** and place the four dowels in each space on the Skull Bottom model **[2]**.

5.10.1. Talent placing hemisphere(s) into upper part of tumor piece

5.10.2. Dowel(s) being placed

5.11. Then place the skull top model on top **[1]**.

5.11.1. Skull top being placed Vid NOTE: USE ACTION FROM 00:04-00:009 AND 00:23-00:29

5.12. If required, the model may then be maneuvered into the desired position to simulate its intraoperative use in surgery **[1]**.

5.12.1. Model being manipulated

Protocol Script Questions

A. Which steps from the protocol are the most important for viewers to see?
4.6., 5.8., 5.9.

B. What is the single most difficult aspect of this procedure and what do you do to ensure success?

n/a

Results

6. Results: Representative Phantom Creation and Evaluation

6.1. Following the protocol as demonstrated, an anatomically realistic phantom, consisting of a patient-specific skull, brain, and tumor, can be fabricated **[1]**.

6.1.1. LAB MEDIA: Figure 2

6.2. The relevant anatomical structures for the phantom **[1]** are segmented using patient MRI **[2]** and CT data **[3]**.

6.2.1. LAB MEDIA: Figures 2A and 2B
6.2.2. LAB MEDIA: Figures 2A and 2B *Video Editor: please emphasize Figure 2A*
6.2.3. LAB MEDIA: Figures 2A and 2B *Video Editor: please emphasize Figure 2B*

6.3. Meshes can then be created for each piece of the model to manufacture the 3D molds as demonstrated **[1]**.

6.3.1. LAB MEDIA: Figure 3

6.4. The cerebellum mold is the most complex to design and assemble **[1]**.

6.4.1. LAB MEDIA: Figure 4

6.5. The skull is the most difficult part to print, as it requires support material **[1]**.

6.5.1. LAB MEDIA: Figure 5A

6.6. The completed phantom **[1]** offers a realistic model of the patient skull **[2]**, brain **[3]**, and tumor **[4]**.

6.6.1. LAB MEDIA: Figure 5 *Video Editor: please emphasize Figure 5A*
6.6.2. LAB MEDIA: Figure 5 *Video Editor: please emphasize brain in Figure 5B*
6.6.3. LAB MEDIA: Figure 5 *Video Editor: please emphasize asterisks in Figures 5B and 5C*

6.7. The two brain hemispheres are produced separately **[1]** and have a realistic appearance, featuring the gyri and sulci of the brain **[2]**.

6.7.1. LAB MEDIA: Figure 5B

6.7.2. LAB MEDIA: Figure 5B *Video Editor: please emphasize ridges in brain in Figure 5B*

6.8. The cerebellum fits comfortably into the base of the printed skull and the brain hemispheres sit on top of this structure **[1]**.

6.8.1. LAB MEDIA: Figure 5C

6.9. The tumor is easily visible in the cerebellum, as the extra contrast added to the tumor results in an off-white color that separates it from the surrounding material to which it is attached **[1]**.

6.9.1. LAB MEDIA: Figure 5C *Video Editor: please emphasize asterisks/area indicated by asterisk*

6.10. The tumor can be visualized in the phantom **[1]** with both CT **[2]** and ultrasound imaging **[3]**.

6.10.1. LAB MEDIA: Figure 6
6.10.2. LAB MEDIA: Figure 6 *Video Editor: please emphasize asterisk in Figure 6A*
6.10.3. LAB MEDIA: Figure 6 *Video Editor: please emphasize asterisk in Figure 6B*

6.11. The patient intra-operative ultrasound data can then be used to compare the phantom images to the real patient images **[1]**.

6.11.1. LAB MEDIA: Figure 2D

Conclusion

7. Conclusion Interview Statements

7.1. **Eleanor Mackle**: When creating the mould, pay particular attention to the position of the cuts within the mould to ensure that the phantom will be able to be removed when it has solidified **[1]**.

7.1.1. INTERVIEW: Named talent says the statement above in an interview-style shot, looking slightly off-camera (2.8.)

7.2. **Jonathan Shapey**: By creating a patient-specific brain phantom, we have been able to test a novel neuronavigation system that can also be used to train neurosurgeons in the use of intraoperative ultrasound **[1]**.

7.2.1. INTERVIEW: Named talent says the statement above in an interview-style shot, looking slightly off-camera