A Liquid Phantom for Validating Hyperspectral Imaging in Brain Tumour Resection

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Abstract: This paper presents a liquid phantom for simulating gliomas in brain tissue. Constructed from PMMA using laser-cut channels guided by segmented surgical images, it simulates vasculature and tumours with blood, Intralipid.

1. Introduction

Brain tumours, especially gliomas, pose a significant challenge in modern medicine. Effective treatment relies on maximizing resection while minimizing damage to healthy brain tissue to prevent neurological deficits. Incomplete resection, however, can lead to recurrence, negatively impacting patient outcomes and the already low efficacy of adjuvant therapies [1, 2]. Hyperspectral imaging shows great promise as a real-time neuronavigational tool for glioma resection, as well as offering advantages over other imaging modalities in identifying glioma grading [3, 4].

Existing brain tumour phantoms often fail to accurately replicate the complex microenvironment of tumours, such as their relationship to surrounding brain structures. 3D printing is often used as a gold standard for accurate microstructure simulation, with some trade-offs. It is a time-consuming process, even for relatively simple designs. For basic prototyping, the enhanced accuracy afforded by 3D printing is often unnecessary, incurring unnecessary cost. Furthermore, a significant limitation of 3D printing in this application is the fixed nature of the material's optical properties, precluding the flexibility required to simulate diverse tissue types and tumour characteristics. Computer Numerically Controlled (CNC) milling, while capable of high precision, shares similar limitations with 3D printing regarding material selection and processing time, making it less suitable for rapid prototyping and iterative design.

To address these limitations, this paper presents the development of a novel liquid phantom and its corresponding design pipeline. This liquid phantom offers increased flexibility, time efficiency and cost when compared to 3D printing and other fabrication methods, such as CNC milling. It provides a valuable tool for validating current and future iterations of optical imaging systems, such as hyperspectral imaging, and the algorithms used to analyse these images. In the following sections, we describe the phantom's design and fabrication, present validation results, and discuss its potential applications.

2. Methods

The phantom is constructed using transparent polymethyl methacrylate (PMMA), chosen for its optical properties that minimize absorption and scattering [5, 6]. To mimic the brain's vascular network, channels are etched into the PMMA using laser cutting, guided by segmented surgical images of brain vasculature. For the tumour, a well was introduced adjacent to the vascular network allowing the introduction of any liquid or gel formulations. The slides reside atop a separate compartment containing a liquid formulation designed to simulate healthy brain tissue. The phantom fabrication process followed this pipeline: 1) Surgical image segmentation; 2) Conversion of the segmented image to a vector graphics (SVG) format; 3) Editing of the SVG file to incorporate vascular channels and remove isolated regions (islands) 4) Addition of a "tumour" well to the SVG file; and 5) Laser cutting of the PMMA substrate using the modified SVG design.

2.1. Segmentation

Brain tissue was segmented as in [7] with the following steps. Using OpenCV (v4.8.1), a colour image was converted to grayscale. A binary image was generated via Gaussian adaptive thresholding on the grayscale image (5mm block size, equivalent to 69 pixels at 0.073mm/pixel resolution). Specular reflection artifacts were removed from by thresholding. Small vessels were segmented by morphological opening (7-pixel diameter disk) of the binary image, followed by morphological closing to obtain the large vessel mask. XOR operation between the binary image and the large vessel image isolated the small vessel mask. Unclassified pixels comprised the gray matter mask.

2.2. Vector conversion and cutting

The image segmentation was used to guide the etching of channels onto transparent PMMA panels. The segmented vascular masks served as a blueprint for laser etching channels onto the PMMA sheets. The large vessel mask, initially rasterized (PNG), was vectorized (SVG) using Inkscape's bitmap tracing functionality with brightness thresholding; a step necessary for compatibility with the laser cutting system. Blood vessels were interconnected to eliminate isolated segments ("islands") ensuring smooth, continuous channels for uniform and efficient perfusion with the desired recipe. Transparent PVC masking tape with acrylic adhesive was used to cover both sides of the resulting cuts, establishing a watertight and airtight seal. Small vent holes were incorporated along the channel edges for air bubbles to escape.

Fig. 1. Original RGB image (left). Segmented binary raster image (centre) and corresponding traced vector image (right), including the tumour well (purple).

3. Results

Figure 2 shows a representative example of the fabricated PMMA slides, filled slides, and the final configuration atop a brain-simulating liquid phantom composed of Intralipid 20%, and human purified red blood cells (pRBC). The laser-etched channels replicate the vascular network derived from segmented surgical images shown in Figure 2. The distinct tumour well allows for introduction and separation of the tumour-simulating liquid, methemoglobinemic blood here, from other compartments as well as the liquid below.

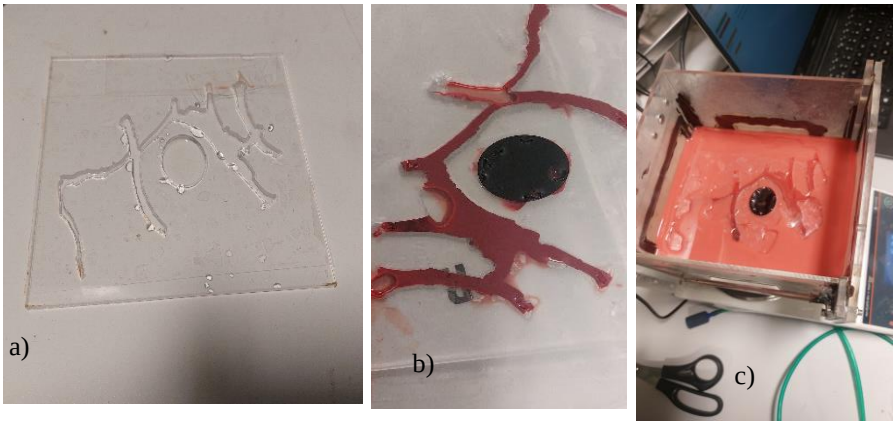

Figure 2: Assembly of the modular liquid phantom. (a) Laser-etched PMMA slide. (b) The same slide after filling the vascular channels with oxygenated blood and the tumour well with methemoglobinemic blood. (c) The fully assembled phantom, showing the liquid-filled slide placed on a brain tissue phantom.

3. Conclusions

This paper presents the development and characterization of a novel modular liquid phantom for simulating gliomas within brain tissue. The phantom, fabricated using laser-etched PMMA, incorporates realistic vascular networks derived from segmented surgical images and distinct tumour wells for precise tumour simulation. While some phantoms utilize complex manufacturing techniques or 3D printing for accurate microstructure simulation, our laser-cutting based approach simplifies fabrication and reduces cost and time in the prototyping phase. Furthermore, the integration

of vascular channels derived from real surgical data enhances the realism of our phantom compared to models with simplified or idealized vascular structures.

3.1. Limitations

Although this method offers benefits in terms of speed and cost, certain limitations should be acknowledged. While the laser cutting process allows precise etching of vascular channels, the inherent two-dimensionality of the technique restricts the creation of complex, three-dimensional vascular structures. Furthermore, the precision achievable with laser cutting, while suitable for this application, is generally lower than that of 3D printing or other more advanced fabrication methods. This limitation is compounded by the material properties of PMMA, which can exhibit localized melting and unpredictable deformation near the cutting area, potentially affecting the accuracy of the finest channel features, as well as restricting the ability to etch small vessels and capillaries. This issue, while present in all situations, is mitigated by lowering the laser power albeit with a significant time trade-off.

3.2. Future work

Future work should include quantitative assessment of the phantom's performance with a hyperspectral imaging system to validate its effectiveness. Furthermore, incorporating a metabolically active component, such as a yeast culture, within the tumour well could enhance the realism of the tumour simulation. Finally, integrating a dynamic perfusion system, using tubing and a pump, would automate the filling and emptying of the vascular channels, eliminating the current manual process and enabling more complex simulations.

4. References

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