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Development of a Realistic Brain Phantom for Medical Education: An Ethical and Technical Alternative to Animal Testing

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Abstract. This study presents the development of a realistic brain phantom as a humane, practical alternative to animal use in medical training, in line with the 3R principles and Directive 2010/63/EU. The phantom is designed to support ultrasound-based education for diagnostic and interventional procedures while improving patient safety through controlled, repeatable practice. High-resolution CT data were converted to CAD models and additively manufactured as moulds; a gelatin-based soft-tissue matrix with glycerin and potassium sorbate provides elasticity and durability. Functional features include fluid-fillable ventricular structures enabling drainage and puncture simulations, and an integrated high-density tumour insert to model advanced scenarios.

Ultrasound evaluation demonstrated clear echogenic differentiation between tumour, ventricles, and surrounding tissue, confirming the model's imaging fidelity and suitability for hands-on training. The phantom proved cost-efficient and reusable, facilitating standardised teaching of complex procedures without ethical approval barriers. A limitation is the material's gradual mechanical instability under repeated probe contact, motivating investigations into synthetic or hybrid matrices to enhance longevity and reuse.

Overall, the brain phantom constitutes an ethical, technically robust, and resource-efficient training tool that addresses critical needs in healthcare quality and safety by reducing avoidable errors through simulation-based competence development.

Introduction

The use of animals in medical education remains the subject of ethical controversy and is increasingly questioned. European Directive 2010/63/EU explicitly mandates minimisation of animal use according to the 3R principles (replacement, reduction, refinement) [1]. Beyond ethics, practical and pedagogical arguments have gained importance: organ phantoms enable realistic simulation of anatomy and pathophysiological conditions, support standardised training, and can be deployed without ethics approvals or animal facilities.

Current data on treatment errors highlight the urgency for effective, repeatable simulation training. In 2023, medical services in Germany assessed 12,438 suspected medical error cases; an error was confirmed in 28.9% (3,595 cases), with harm established in 3,160 cases and a causal link in 2,679 cases [2]. Inexperience and prospective memory failures are recurrent contributors to critical incidents [3]. High-fidelity simulation with organ models offers controlled environments for deliberate practice, improving team communication, cognitive processing, and patient safety [3].

This work introduces an anatomically and functionally realistic brain phantom tailored for ultrasound-based training. The model integrates fillable ventricles for cerebrospinal fluid (CSF) simulations and a tumour insert to enable diagnostic and interventional scenarios, thereby addressing ethical imperatives and safety-critical training needs.

Material and Methods

Anatomical modelling and mould fabrication

Three-dimensional brain morphology was reconstructed from high-resolution computed tomography (CT) data using CAD software. The CAD volumes were used to fabricate a multi-part negative mould via fused deposition modelling (FDM) on a BambuLab X1 Carbon printer using white PLA filament (Material4Print) [4]. The final mould comprises seven components: two base plates, two ventricular structures, a tumour placeholder, and two hemispheric shells. Ventricular components are mounted on the base plates to reproduce spatial topology accurately, as illustrated in Figure 1.

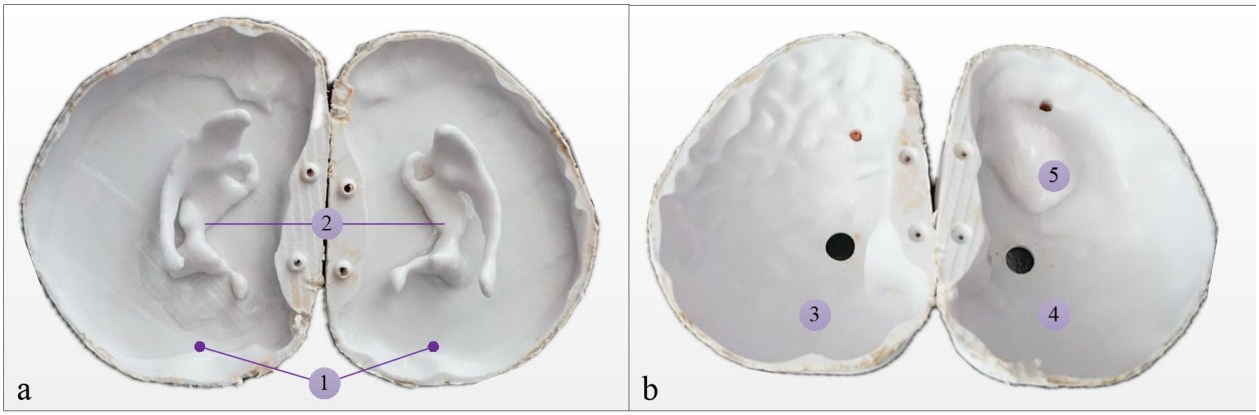

Fig.1. Components of the casting mould for replicating a human brain. a) Base plate with the left and right hemispheres (1) and the 3D-printed ventricles (2). b) Right hemisphere (3) and left hemisphere (4) with integrated placeholder for the tumour (5) in the left hemisphere.

Phantom matrix and additives

A soft-tissue analogue was prepared from animal gelatin (Bloom 250) to approximate the mechanical and acoustic properties of brain tissue [5]. Potassium sorbate served as an antimicrobial preservative [6], and glycerin was added as a humectant to maintain elasticity and reduce water loss [7]. A higher-concentration gelatin solution formed the tumour insert to increase density and echogenicity. Adhesive gelatin was applied at elevated temperature to bond the hemispheres within the negative mould, ensuring dimensional stability during curing.

Ventricular system and interventional access

Two flexible silicone tubes with Luer-lock connectors were embedded in one ventricle to permit controlled filling and emptying with water, simulating CSF circulation and enabling drainage/puncture training. The system supports ventriculostomy and CSF aspiration under ultrasound guidance.

Results

A mobile ultrasound system (Sonosite Titan; FUJIFILM Sonosite Inc., USA) equipped with a linear-array transducer is used to image the brain phantom. The examination targets the left hemisphere, which contains the tumour insert, with the transducer (1) positioned superficially on the hemispheric surface, as shown in Figure 2. The sonogram demonstrates clear echogenic differentiation: the tumour (2) appears hyperechoic, whereas the surrounding phantom tissue (3) exhibits comparatively low echogenicity (anechoic), enabling reliable delineation of lesion boundaries.

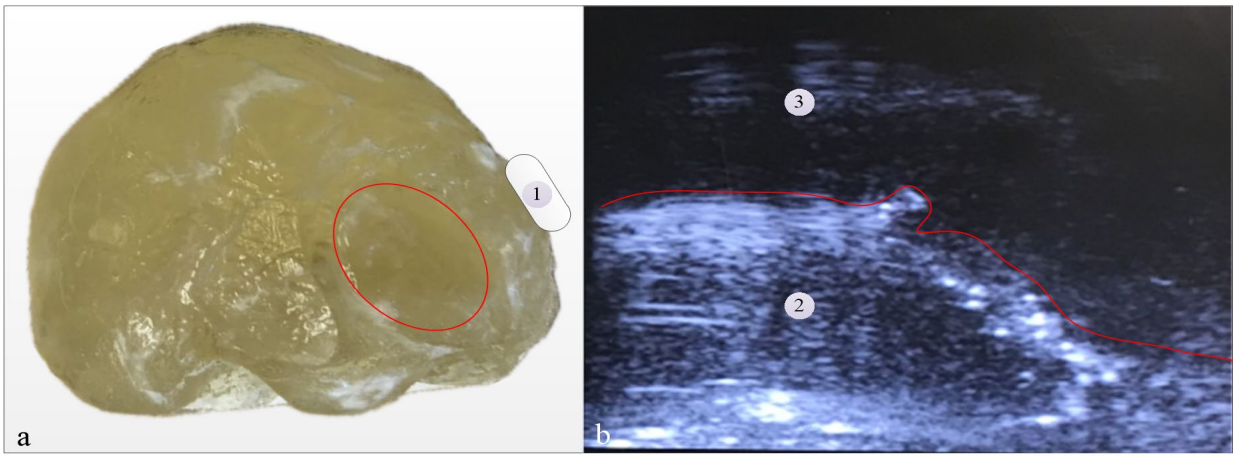

Fig. 2. a) Phantom model of the left hemisphere of the brain, with the linear ultrasound transducer (1) placed in a standardized position on the surface of the right hemisphere. b) The sonogram shows a clear differentiation between the simulated tumour structure (2) and the surrounding phantom tissue (3). The tumour is displayed as echogenic compared to the surrounding tissue. The surrounding tissue is displayed as anechoic.

Figure 3 demonstrates targeted probe positioning and margin delineation in the brain phantom: the ultrasound probe (2) is placed directly above the embedded tumour (1). The corresponding sonogram shows the tumour (3) as distinctly hyperechoic relative to the surrounding phantom tissue (4), enabling precise margin delineation. A local zone with attenuated interface contrast (5) is evident, attributable to preparation-induced partial bonding of the tumour surface to the adjacent matrix, which blurs margins and constitutes a relevant imaging artefact.

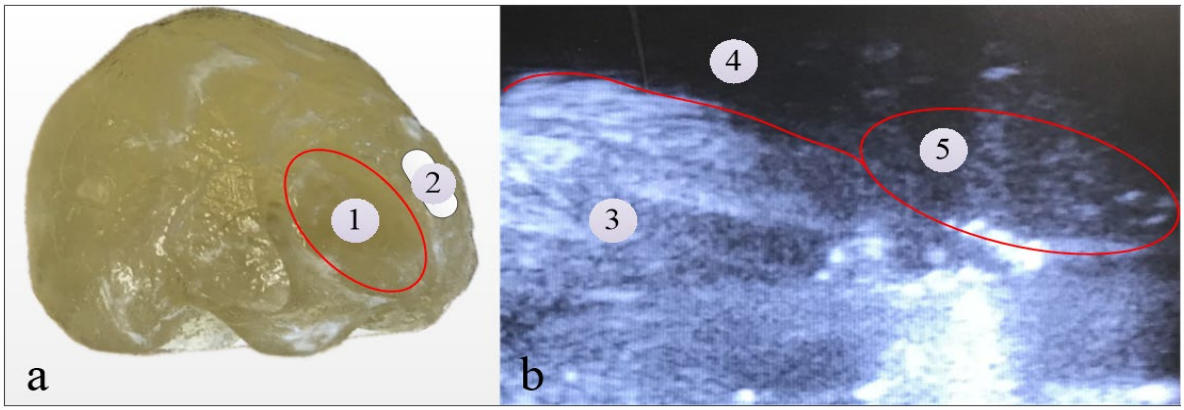

Fig. 3. a) Representation of the phantom brain with embedded tumour (1) and positioning of the ultrasound probe (2) on the surface. b) Corresponding ultrasound image with echogenic tumour structure (3), surrounding phantom tissue (4) and an area with blurred tumour margins (5).

Figure 4 evaluates the sonographic representability of intracranial fluid spaces by targeting the water-filled ventricle (1) in the right hemisphere of the brain phantom. In the corresponding ultrasound image, the ventricle appears echo-poor/anechoic and sharply contoured (3) against the surrounding echogenic phantom tissue (2), validating the model's anatomical and functional realism and its suitability for ultrasound-guided simulation of cerebrospinal fluid compartments. This configuration enables faithful reproduction of ventricular pathology and supports training of intervention-related scenarios, including ventriculostomy and cerebrospinal fluid puncture under sonographic guidance.

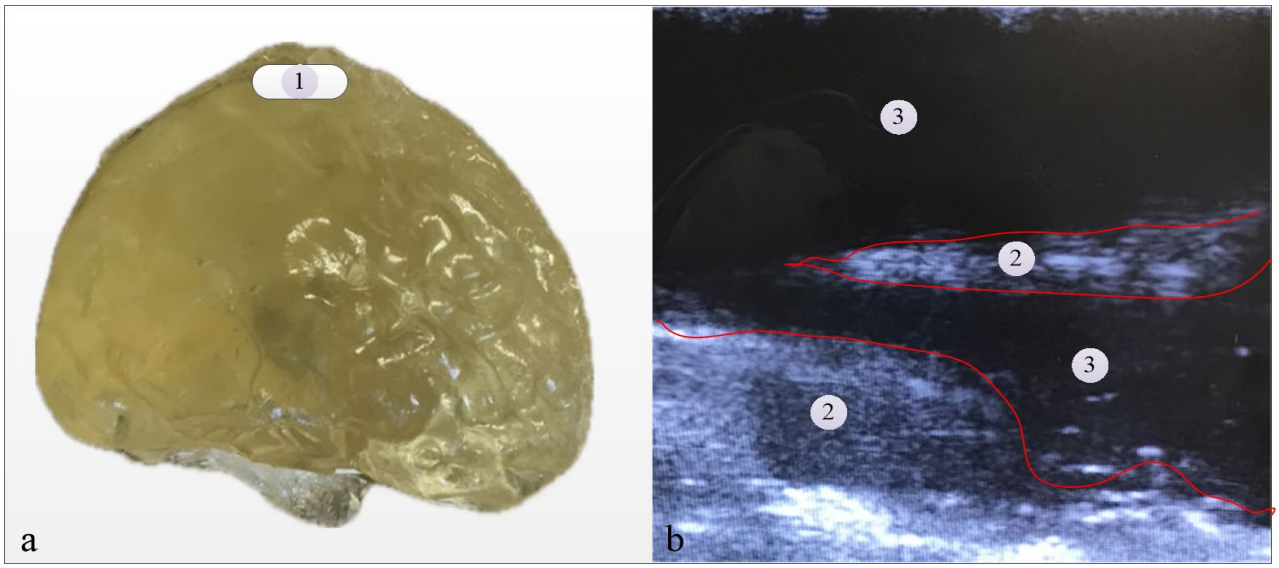

Fig. 4. a) Positioning of the ultrasound probe above the fluid-filled ventricle (1) for targeted detection of the intracranial fluid structure. b) Sonographic image with echogenic phantom tissue (2) and echo-poor imaging of the ventricles (3). The clear contrast allows clear differentiation between the ventricular space and the surrounding tissue.

Repeated ultrasound examinations lead to progressive mechanical instability of the phantom. Detailed sonographic assessment of medial hemispheric structures requires removal of portions of the outer support mould to permit direct access to internal regions. The resulting direct probe pressure imposes local mechanical stress on the gel matrix, causing structural deformation and, in some cases, partial failure of the construct.

Discussion and Outlook

Ethical, practical, and educational value

The brain phantom provides a credible replacement for animal models in accordance with Directive 2010/63/EU and the 3R framework [1]. It is low-cost, rapidly manufacturable, and reusable, thereby reducing logistical barriers to high-frequency practice and enabling standardised, competence-oriented training in risk-bearing procedures. By permitting controlled, repeatable rehearsals of ultrasound-guided diagnostics and interventions, the model addresses known contributors to adverse events—limited experience and prospective-memory failures—and is consistent with training modalities associated with fewer errors and improved patient safety [2,3]. The organ-specific topology, functional ventricles, and robust sonographic contrast collectively enhance face and construct validity, supporting translational relevance from simulation to clinical practice.

Comparison to common approaches

Conventional gelatin blocks and generic commercial phantoms rarely capture organ-level geometry or offer controllable intraventricular flow. The present design integrates anatomically faithful ventricular architecture with fill-and-drain functionality and a high-density tumour insert to enable graded scenario complexity. Relative to undifferentiated ultrasound gels, the CAD-driven, organ-congruent geometry improves spatial orientation and topographic learning pertinent to neurosurgical workflows. These attributes position the phantom for rigorous validity studies (face, content, construct, and, ultimately, criterion validity) and for harmonised skills assessment across centres.

Limitations

Progressive degradation under repeated probe loading indicates limited mechanical resilience of the gelatin matrix, constraining intensive or prolonged use. The absence of skull-like and meningeal

layers reduces fidelity for transcranial insonation and alters probe–tissue interaction. Microanatomy (e.g., small vessels, cortical lamination) remains simplified. Longevity and reproducibility may depend on hydration, temperature, and cleaning/disinfection protocols, as well as printer/material variability. Future evaluations should quantify mechanical (elastic recovery, tear resistance) and acoustic properties (attenuation, speed of sound, backscatter) against physiological targets and report inter-batch variability.

Future development

Development should prioritise synthetic or hybrid matrices (e.g., synthetic gelatin analogues, alginate/PVA systems, cryogels) to enhance toughness, elastic recovery, shelf life, and acoustic matching. Layered constructs that represent scalp, skull, and dura would recreate impedance transitions and realistic attenuation. Swappable pathology modules (cystic, necrotic, calcified) and embedded sensors (pressure, flow, force) could enable objective metrics and automated feedback. Integration with AR/VR and AI-assisted guidance promises adaptive, data-driven learning. Multicentre studies with predefined performance endpoints, mapping to competency-based curricula, and open dissemination of CAD/print files would support scalability, external validity, and equitable adoption. A life-cycle assessment should quantify cost, environmental impact, and reductions in animal use.

Conclusions

An anatomically grounded, ultrasound-compatible brain phantom is presented that unites organ-specific geometry, fluid-fillable ventricular architecture, and a high-contrast tumour insert to enable standardised, repeatable training aligned with Directive 2010/63/EU and the 3R principles [1]. The phantom reliably produces distinct echogenic signatures for ventricular and tumour structures, supports hands-on rehearsal of ultrasound-guided diagnostics and interventions, and lowers barriers to frequent practice through low cost and rapid manufacture. In aggregate, these attributes position the model as a pragmatic lever for error reduction and patient-safety improvement in competence-based medical education, consistent with evidence linking structured simulation to fewer errors [2,3].

Durability constraints of gelatin under repeated probe loading and the absence of skull- and meningeal-like layers limit fidelity for transcranial insonation and prolonged high-intensity use. These findings motivate evaluation of synthetic or hybrid matrices with improved toughness and elastic recovery, as well as layered constructs that reproduce realistic impedance transitions. Modular pathology inserts and embedded sensing (force, pressure, flow) can enable objective performance metrics and automated feedback, strengthening construct and criterion validity.

To maximise translational impact, future work should include multicentre validation with predefined endpoints, alignment to competency-based curricula, and open dissemination of CAD and print files to facilitate reproducibility and equitable adoption. Life-cycle and cost analyses should quantify economic and environmental benefits alongside reductions in animal use. With these developments, the platform matures into a scalable, ethically robust alternative to animal models that advances technical skill acquisition and system-wide patient safety.

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