2023 I-RIM Conference
October 20-22, Rome, Italy
ISBN: 978-88-945805-4-9
10.5281/zenodo.10722466

Design and Fabrication of a Phantom Head for Robotic Neurosurgery Simulation

C. Abello[1,2,*], F. Mariano[1,3,*], N. Kamal[1], G. Berselli[1,4], E. De Momi[3], Gianluca Piatelli[2] and L. S. Mattos[1]
[1]*Biomedical Robotics Lab, ADVR, Istituto Italiano di Tecnologia*, Genoa, Italy
[2]*Istituto Giannina Gaslini*, Genoa, Italy
[3] *DEIB, Politecnico di Milano*, Milan, Italy
[4]*DIME, Università di Genova*, Genoa, Italy
carola.abello@iit.it, federicomariano.mariano@polimi.it, engr.nabeel.iqtm@gmail.com,
giovanni.berselli@unige.it, elena.demomi@polimi.it, leonardo.demattos@iit.it

***Abstract*—Phantoms are essential tools for planning and simulating surgical operations, testing new medical instruments and training purposes. Current simulators, including human cadavers, animal models and virtual reality systems, are expensive and relatively inaccessible. The aim of this study is to design and realise a low-cost 3D model of a human head made for paediatric neurosurgery. Starting with Magnetic Resonance Imaging (MRI) of a patient's head, a phantom was fabricated by combining nylon 3D printing and the use of agar to mimic skull and soft tissue. In addition, tumor volumes made of vaseline and silicon skin were added to the phantom to allow real MRI of the phantom head and thus enable surgical navigation. The phantom was then used to test the functionality of a new paediatric neurosurgery robot, by serving as a realistic model of child's head. This method is cost-effective and provides a reproducible model suitable for both surgical simulation and training purposes.**

I. INTRODUCTION

Phantoms are useful tools in surgery, as they accurately replicate human anatomy and facilitate the simulation of various clinical scenarios. They have proven to be invaluable resources in experimental and educational applications [1]. Our main objective is to develop a realistic phantom that would enable neurosurgeons to evaluate, safely and in a controlled manner, an innovative robot designed for paediatric neuroendoscopy [2]. Among the many techniques used for phantom fabrication, gelatin has emerged as one of the most commonly employed materials for simulating soft tissue [3]. Gelatin is easily accessible and visible in Magnetic Resonance Imaging (MRI). However, it poses challenges because of its deterioration, requiring careful refrigeration, and it can not be reused multiple times. In light of these limitations, this study aimes to develop a novel phantom head using agar, a natural gelling agent derived from red seaweed [4]. The use of agar allows us to create a gel that faithfully replicates the properties of human brain tissue without the concerns of deterioration over time [3] [5]. This advancement opens up new possibilities for long-term use and reproducibility in various medical procedures. In our case study, vaseline balls were incorporated into the agar-based phantom to simulate the presence of tumors.

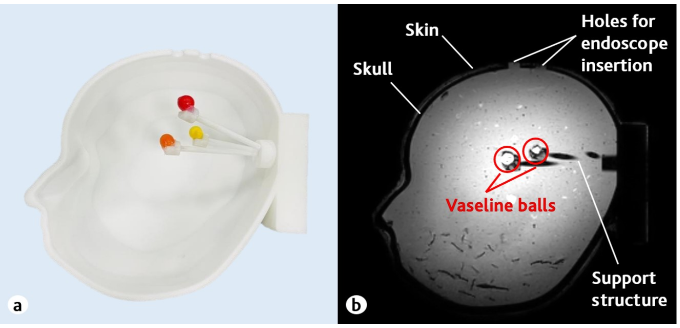

Fig. 1. (a) Nylon half mold with inner support structure to hold the vaseline balls; (b) MRI of the phantom head illustrating the structures of interest;

II. MATERIALS AND METHODS

A. Phantom fabrication

The phantom was constructed using a combination of materials that simulate the various anatomical structures. Specifically, the use of agar to mimic internal tissues and a nylon structure allowed the creation of a faithful replica of the skull and cerebral tissues. Moreover, the choice of materials was based on their MRI visualization capability, tissue-like consistency reproduction and reusability without loss of properties. A meticulous model of the skull was developed using Computer-Aided Design (CAD) software (Creo Parametric), with reference to a child's MRI images. A support structure was created within the skull cavity, wherein spheres, made with balloons and vaseline, were incorporated to simulate the presence of tumors (Fig. 1). Subsequently, the skull was fabricated using nylon selective laser sintering technology. The two half molds were securely bonded and sealed with silicone and the interior cavity was filled with a solution of water and agar. The preparation of the mixture was carried out following a specific procedure: 750ml of tap water was mixed with 38g of agar, then the water-agar suspension was heated in the microwave for 5 minutes and stirred until a thick, gelatinous mixture was obtained. Finally to simulate the presence of skin, a thin layer of silicone (Pro-lastix 10 shore A, Prochima) was applied to the outer surface of the phantom.

---

* The authors contributed equally.

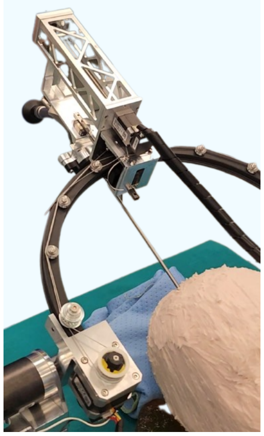

Fig. 2. IIT paediatric neurosurgery robot and phantom head during the test at Gaslini Children's Hospital.

B. Robot functioning

In 2021, the Istituto Italiano di Tecnologia (IIT) developed an innovative robot designed for paediatric neuroendoscopy [2]. The new robotic system can orient, hold and insert safely the endoscope at any point in the skull, reducing risks for the patient. The basic mechanism is characterized by a semi-circular track motion system (Fig. 2) and a translation mechanism for a total of 6 actuated degrees of freedom (DOFs). More specifically, the robot allows i) translation along the Cartesian axes, ii) rotations of the arch (Pitch) and endoscope holder along the arch itself (Yaw), and iii) insertion of the endoscope inside the cranial cavity.

This design enables the placement of the Remote Center of Motion (RCM) at the incision point on the patient's head [6]. Specifically, the RCM designates the fixed pivot point where the endoscope remains motionless, regardless of any instrument rotation. This constraint has several advantages including fewer complications for patients and greater accuracy.

C. Robot assessment

The experimental protocol involves the following steps for precise execution of the robot test procedure:

i) MRI scan: An MRI scan of the phantom head is performed to visualize cranial and internal structures (Fig. 1);

ii) Head positioning: The phantom is placed on the operating bed, following standard practices for paediatric patients;

iii) Neuronavigation system: Registration with the neuronavigation system is performed to ensure accurate guidance during subsequent steps;

iv) Positioning and insertion of the endoscope: Once the target of interest is chosen, using the robot and the neuronavigation system, precise positioning and orientation of the neuroendoscope are performed. Afterwards, the insertion of the surgical instrument is executed. The success of this step is contingent upon several factors, such as the accuracy of the robotic system evaluated using International Standard ISO 230-2:

- Yaw: 0.47°;
- Pitch: 1.023°;
- Insertion of the endoscope: 503μm.

v) Verification: Finally, the accuracy of the endoscope in reaching the chosen target is evaluated.

III. RESULTS

A team of neurosurgeons at Gaslini Children's Hospital employed the fabricated phantom as a testing tool to evaluate the new robot's operational effectiveness and capabilities. MRI images proved the realism of the phantom, enabling precise visualization of tumors, skin and internal tissues. This provided guidance for surgeons to identify the most suitable insertion point and correct orientation of the endoscope for tumors removal. Using the neuronavigation system, neurosurgeons successfully navigated to the vaseline spheres, validating the robot's capabilities. Observation of the robot's performance revealed the complexity of precise positioning with respect to Cartesian axes. However, endoscope insertion was observed to be linear, without significant oscillations, ensuring precision during surgical procedures. The phantom experimentation also confirmed that agar effectively simulates the consistency of internal tissues, providing valuable tactile feedback for surgeon training and practice. Furthermore, its reusability and stability in the refrigerator for extended durations make it a perfect choice for long-term simulations, enhancing its practicality and cost-effectiveness.

IV. CONCLUSION

The phantom developed in this study proved to be an effective tool for testing a new robot for paediatric neurosurgery. Its anatomical fidelity, combined with MRI visualization and tactile feedback provided by agar, offers a safe and controlled environment for testing and assessing the robot's precision. Regarding the robot's performance, the evaluation has revealed significant potential for a future paediatric neurosurgery robot. The integration of the phantom in the testing process has been invaluable in identifying strengths and areas of improvement in the new robot's capabilities. Through continued refinement and development, we are optimistic that the combined use of the phantom and the new robot will pave the way for more advanced and effective paediatric neurosurgical procedures.

REFERENCES

[1] A. Müns, J. Meixensberger, and D. Lindner, "Evaluation of a novel phantom-based neurosurgical training system," Surgical Neurology International, December 2014.

[2] N. Kamal, "Design and development of a robotic system for pediatric neurosurgery," Istituto Italiano di Tecnologia, unpublished.

[3] M. Earle, G. De Portu, and E. DeVos, "Agar ultrasound phantoms for low-cost training without refrigeration," African Journal of Emergency Medicine, 2016, pp. 18–23.

[4] Y. H. Pandya, M. Bakshi, and A. Sharma, "Agar-agar extraction, structural properties and applications: a review," The Pharma Innovation Journal, 2022, pp. 1151–1157.

[5] V. Katiyar, et al., "A high-fidelity agar-based phantom for ultrasonography-guided brain biopsy simulation: a novel training prototype with visual feedback," World Neurosurgery, 2022, pp. 333–343

[6] R. C. O. Locke and R. V. Patel, "Optimal remote center-of-motion location for robotics-assisted minimally-invasive surgery," IEEE International Conference on Robotics and Automation, Rome, April 2007.