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Fabrication of a Flexible, Transparent, and Durable 3D Neuroanatomical Model for Teaching Neuroanatomy using Silicone Rubber and Epoxy Resin

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ABSTRACT

Neuroanatomy education relies heavily on cadaveric specimens, histological slides, and two-dimensional illustrations, which are limited by scarcity, lack of durability, and insufficient visualization of three-dimensional neuronal structures. To address these limitations, this study aimed to develop a flexible, transparent, and durable three-dimensional model of a neuron, incorporating labeled subcellular components, for hands-on neuroanatomy teaching. A master prototype of a neuron was first created on a polystyrene board, representing the cell body, axon, dendrites, and axon terminals. Silicone rubber molds were then prepared from the prototype, and epoxy resin casting was employed to fabricate the transparent cell body. Subcellular organelles—including the nucleus, mitochondria, and Nissl bodies—were modeled using colored polymer clay and embedded within the cell body. Axons and dendrites were constructed using pigment-coated wool threads and copper wire, while the myelin sheath was fabricated via a silicone mold and epoxy resin, with grooves simulating Schwann cell attachment sites. The assembled neuron model demonstrated clear visualization of all components, with excellent flexibility, transparency, and durability. The embedded organelles were distinctly visible, and color-coded labeling facilitated easy identification of neuronal structures. Compared to traditional teaching resources, this model offers a multi-scale, hands-on tool for understanding neuronal morphology, axonal and dendritic organization, and subcellular architecture. By combining cost-effective materials, reproducible fabrication techniques, and anatomical accuracy, the model represents a novel contribution to neuroanatomy education. This approach can be extended to fabricate other cellular or tissue models, providing a practical, durable, and pedagogically effective alternative for neuroscience teaching and research training.

Keywords: **n**euroanatomy, neuron model, 3D fabrication, silicone rubber, epoxy resin

INTRODUCTION

Neuroanatomy forms a fundamental part of medical and biomedical education, providing essential insights into the organization, structure, and function of the nervous system. A thorough understanding of neuronal morphology—including the cell body, axon, dendrites, myelin sheath, and organelles such as the nucleus, mitochondria, and Nissl bodies—is critical for both basic neuroscience and clinical disciplines such as neurology, neurosurgery, and neuropathology [1,2]. Traditionally, neuroanatomical education has relied on cadaveric specimens, histological slides, and two-dimensional illustrations. While these resources are valuable, they have notable limitations. Cadaveric specimens are scarce, non-renewable, and often unavailable in sufficient quantity for repeated hands-on learning [3, 4, 5]. Histological slides provide only two-dimensional cross-sectional views that fail to convey the full three-dimensional complexity of neuronal structures, and illustrations cannot fully capture the spatial relationships between cellular components. Consequently, there is a growing need for reliable, durable, and anatomically accurate three-dimensional models that can enhance both teaching and learning in neuroanatomy [6, 7].

Advances in three-dimensional (3D) printing and molding technologies have transformed anatomical education and preclinical research by enabling the creation of patient-specific or specimen-specific phantoms and replicas. Nilsson *et al.* [8] demonstrated the fabrication of patient-specific cerebral arterial phantoms using 3D-printed water-soluble molds and transparent silicone rubber (PDMS), achieving accurate replication of complex vascular geometries suitable for in vitro testing and flow studies. Similarly, Bisighini *et al*.[9] employed a spin–dip coating technique to produce hollow, compliant vascular phantoms for evaluating endovascular devices. These studies highlighted the potential of 3D printing and silicone molding to generate transparent, flexible, and anatomically precise models. Other studies have shown that 3D-printed anatomical models, including brain and vascular structures, improve learner engagement and understanding of complex spatial relationships **Error! Reference source not found., Error! Reference source not found.**. Sushobhana *et al* [10] explored the use of silicone rubber and epoxy resin molds to replicate soft brain tissues for anatomical teaching. While these models were durable, cost-effective, and visually faithful to gross specimens, they were limited to organ-level structures and lacked the cellular and subcellular details necessary for a deeper understanding of neuronal morphology and function.

Despite these advances, there is currently no report of a three-dimensional, flexible, transparent, and labeled neuronal model that integrates the key components of a neuron, including the nucleus, mitochondria, Nissl bodies, axon, dendrites, myelin sheath, and axon terminals, in a format suitable for hands-on teaching and visualization at multiple scales. The development of such models offers several advantages: enhanced visualization of cellular architecture in three dimensions, durable and reusable teaching tools that overcome the scarcity of cadaveric specimens, and the ability to integrate color-coded labels and components to facilitate active learning and improve retention of complex neuroanatomical concepts [12, 14].

To address these gaps, this study aimed to develop a flexible, transparent, and durable three-dimensional neuroanatomical model using silicone rubber for mold preparation and epoxy resin for casting. The model incorporates labeled subcellular components and neuronal processes, enabling accurate representation of the structure of a neuron at both macro- and micro-scales. This approach represents a novel contribution to the field, bridging the gap between gross anatomical models and microscopic neuroanatomical structures, and providing a practical, cost-effective, and pedagogically powerful tool for neuroanatomy education and research training. By combining flexibility, transparency, and durability, the model allows for hands-on exploration of neuronal morphology in a manner that has not been previously reported in the literature.

MATERIALS AND METHODS

Study design

This descriptive experimental study was conducted in the Department of Anatomy at University of Calabar, Nigeria, focusing on the development of a three-dimensional, flexible, transparent, and durable neuroanatomical model for educational purposes. The study involved the stepwise fabrication of neuron components, including the cell body, axon, dendrites, myelin sheath, and subcellular organelles, using silicone rubber and epoxy resin, following approaches adapted from previous anatomical modeling studies [10, 8].

Materials

The materials used in this study included industrial silicone rubber (Part A and Part B, hardener), epoxy resin (Part A) with its corresponding hardener (Part B), polystyrene boards for prototype modeling, fine sandpaper for surface finishing, plastic plates and wooden boards for mold setup, machine oil as a mold release agent, plasticine clay for sealing, wool threads to simulate axons and dendrites, colored polymer clay for representing subcellular structures such as the nucleus, mitochondria, and Nissl bodies, yellow pigment resin for coating axons, and an electric drill for tunnel and groove formation.

Prototype creation

A master prototype of a neuron was created on a polystyrene board. Dimensions of the cell body, axon, and dendrites were drawn with grid lines to outline their profiles. Carving was performed using cutting tools to achieve the desired shapes, followed by priming and smoothing with fine sandpaper to remove surface irregularities. The use of polystyrene boards for anatomical prototypes has been previously described for organ-level replication [10].

Figure 1: Prototype of a neuron

Silicone mold preparation

Industrial silicone rubber was prepared by mixing 1 kg of Part A with 20 g of hardener (Part B) in a clean container. The prototype was coated with machine oil to facilitate demolding and mounted on a transparent plastic plate affixed to a wooden board. Plasticine clay was used to seal the base of the plate to prevent silicone leakage. The mixed silicone rubber was poured over the prototype and allowed to cure for 4 hours at room temperature. After curing, the silicone mold of the cell body was carefully demolded. This procedure follows previously reported silicone molding techniques for anatomical models [10, 8].

Figure 2: Silicone mold

Epoxy resin casting

Epoxy resin was prepared by mixing Part A with Part B in a 2:1 ratio. The resin mixture was poured into the silicone mold of the cell body. Pre-formed subcellular components (nucleus, mitochondria, and Nissl bodies) made from colored polymer clay were positioned within the mold at appropriate locations. The mixture was allowed to cure overnight before demolding, resulting in a transparent, durable model of the neuron cell body with labeled organelles. Similar casting techniques using epoxy resin have been previously employed for anatomical replication [10].

Axon and dendrite fabrication

Wool threads approximately 15 cm in length were soaked in a yellow pigment resin mixture (2:1) and removed three times to achieve the desired thickness for the axon. Eight shorter strands (6 cm) were similarly treated and arranged to simulate axon terminals. Dendrites were modeled using copper wires coated with yellow pigment resin and allowed to dry. This approach of using fiber or wire-based frameworks for fine anatomical structures is adapted from techniques described in 3D neuroanatomical and vascular modeling [8, 9].

Myelin sheath fabrication

Prototypes of the myelin sheath were created from polystyrene boards (3 cm length, 1.5 cm diameter) and used to prepare silicone molds following the same protocol as the cell body. Transparent epoxy resin was poured into the mold, and after curing, tunnels were created using an electric drill for axon passage. Minor grooves were drilled into the myelin sheath to allow attachment of Schwann cell representations. Similar mold-based techniques have been described for vascular and soft tissue replication [8, 9].

Assembly

The final neuron model was assembled by inserting the axon through the myelin sheath, attaching dendrites, and positioning axon terminals. Subcellular organelles remained embedded within the cell body, providing accurate visualization of internal neuronal structures. Labels for the nucleus, mitochondria, and Nissl bodies were printed, laminated, and attached to their corresponding components for educational use, following the pedagogical labeling approach described by Sushobhana *et al*., [10].

Model evaluation

The completed model was assessed for flexibility, transparency, and durability, as well as the accuracy of anatomical representation of the neuron and its components. The model was designed to be handled and examined in a classroom setting for teaching neuroanatomy [10].

RESULTS

Model observation

The study successfully produced a three-dimensional, flexible, transparent, and durable model of a neuron, accurately replicating both the macro- and microstructural components of the cell as reported in fig 3. The neuron's cell body, axon, dendrites, myelin sheath, and axon terminals were clearly visualized, with subcellular organelles, including the nucleus, mitochondria, and Nissl bodies, embedded within the transparent epoxy resin and distinctly labeled for educational purposes. The silicone mold enabled precise replication of intricate neuronal features, while the epoxy resin casting provided durability and transparency, allowing unobstructed observation of internal structures. The axon and dendrites maintained structural integrity, and the myelin sheath accurately enveloped the axon with grooves simulating Schwann cell attachment. The model demonstrated excellent flexibility, allowing manipulation without damage, and durability.

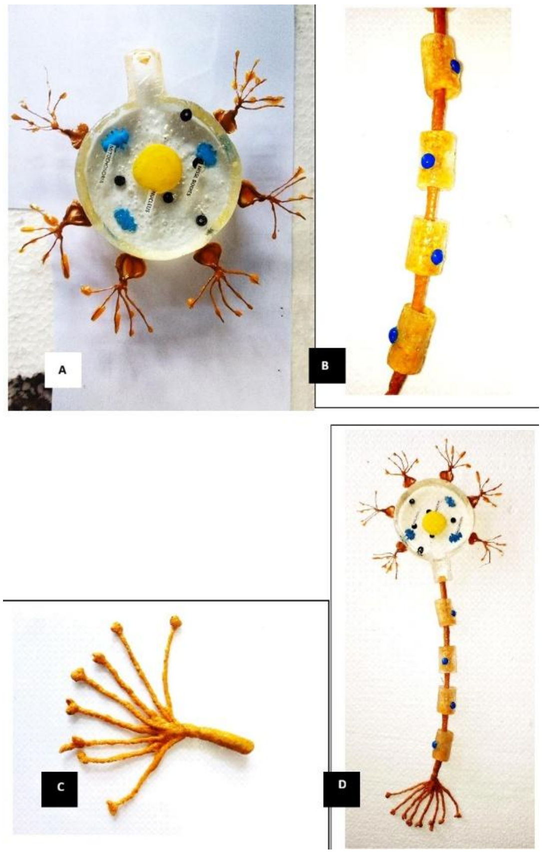

Fig. 3: Three-dimensional neuroanatomical model of a neuron. (A) Cell body: Transparent epoxy resin casting of the neuron's cell body showing embedded and labeled subcellular organelles: nucleus (yellow), mitochondria (blue), and Nissl bodies (black). The mold preserves fine surface details and internal structures. (B) Axon and myelin sheath: The axon (yellow) is encased in a transparent myelin sheath with grooves representing Schwann cell attachment. The myelin sheath was fabricated using a silicone mold and epoxy resin, maintaining flexibility and structural integrity. (C) Dendrites and axon terminals: Dendrites (yellow-coated copper wires) and axon terminals (bundled yellow threads) are attached to the cell body, demonstrating realistic branching patterns and connections. (D) Complete assembled neuron: The cell body, axon with myelin sheath, dendrites, and axon terminals are assembled into a single model. The transparency of the resin allows clear visualization of internal organelles and overall neuron architecture, highlighting the model's utility for neuroanatomy education.

DISCUSSION

The present study successfully developed a three-dimensional, flexible, transparent, and durable neuroanatomical model of a neuron using silicone rubber molds and epoxy resin casting. The model accurately replicated both the macroscopic neuronal morphology and subcellular structures, including the nucleus, mitochondria, and Nissl bodies, while integrating axons, dendrites, myelin sheaths, and axon terminals. This approach represents a novel advancement in anatomical modeling, bridging the gap between traditional organ-level replicas [10] and microscopic neuron visualization required for neuroanatomy education.

The use of silicone rubber for mold fabrication provided the flexibility necessary to capture intricate details of the neuron's surface, while the epoxy resin ensured transparency and durability, allowing repeated handling without structural compromise. These material properties are consistent with previous studies demonstrating the advantages of hybrid molding techniques for anatomical phantoms [8, 9]. Similar approaches have been used in vascular and organ phantoms to achieve precise structural replication and mechanical compliance [16]. However, this study uniquely applied these techniques at the cellular level, highlighting the potential for teaching microscopic structures in a three-dimensional, tangible format.

The inclusion of labeled subcellular organelles within the transparent cell body allowed for enhanced visualization and spatial understanding of neuronal architecture. This aligns with the pedagogical principle that multi-sensory, three-dimensional learning tools improve retention and comprehension of complex anatomical concepts [17, **Error! Reference source not found.**]. Unlike traditional histological slides, which provide only two-dimensional cross-sections, the model enables learners to appreciate the three-dimensional orientation of organelles and processes, such as dendritic branching and axon–myelin interactions.

The fabrication of axons and dendrites using pigment-coated threads and wires provided a durable yet flexible framework that simulates physiological neuronal branching. The myelin sheath design, incorporating grooves for Schwann cell attachment, mimicked functional aspects of neuronal insulation, providing a more realistic representation than prior models of gross brain anatomy [10] or vascular phantoms [8, 9]. This attention to structural detail enhances the utility of the model not only for teaching normal anatomy but also for illustrating neuropathological conditions in which axonal or myelin integrity is compromised, such as multiple sclerosis or peripheral neuropathies [18].

While digital technologies such as virtual reality (VR) and 3D digital models have significantly advanced neuroanatomy education by providing detailed, scalable visualizations, their widespread implementation can be constrained by factors such as high costs, limited access to equipment, and the absence of tactile feedback necessary for kinesthetic learning. In our resource-limited setting, physical 3D models serve as practical and effective educational tools that offer tangible, hands-on experience, which can enhance spatial understanding and retention [20]. Although these models lack the microscopic detail and realistic texture of actual tissue, they are cost-effective, durable, and reusable, making them suitable for repeated classroom use [21]. Nonetheless, physical models are not without limitations, including reduced haptic realism and potential material degradation [22].

The hybrid use of silicone and epoxy resin ensures both flexibility in mold preparation and durability in final casting, making the model suitable for repeated classroom handling without degradation. Its transparency allows direct observation of embedded structures, an advantage over opaque models or traditional dissections. Furthermore, the labeled organelles provide a self-guided learning experience that complements lectures, digital resources, and histology slides.

The implications of this work extend beyond anatomy education. The model could be adapted for neuroscience research training, particularly in understanding neuronal morphology, axon–dendrite interactions, and structural changes in disease models. Additionally, the methodology described here could be applied to fabricate other cellular or subcellular models, such as glial cells, synapses, or vascular microstructures, thereby expanding the scope of 3D anatomical and histological modeling.

While student acceptance and the influence of these models on learning and examination performance are important considerations, they were beyond the scope of our current study, which focused primarily on the development and initial evaluation of the models. Future research should explore these aspects to better understand how such models impact student engagement, comprehension, and academic performance, ultimately informing their integration into neuroanatomy education.

In summary, this study presents a novel, flexible, transparent, and durable 3D model of a neuron that integrates labeled subcellular organelles and realistic neuronal processes. The model demonstrates accurate replication of both macro- and microstructural features, combining the advantages of silicone rubber molds and epoxy resin casting. Its structural fidelity, durability, and educational utility make it a valuable tool for neuroanatomy teaching, bridging the gap between gross anatomical models and microscopic visualization.

CONCLUSION

The 3D neuron model developed in this study represents a significant advancement in anatomical education. By combining flexibility, transparency, and durability with labeled cellular components, the model allows for hands-on, multi-scale learning of neuronal structure and organization.

Authors' contributions

C.A.A: conceived and designed the study. C.A.A and E.I.O: drafted and critically revised the manuscript. E.N.T. and J.C.C: carried out the experimental work, including prototype fabrication, silicone mold preparation, epoxy resin casting, assembly of the neuron model, and preparation of labeled subcellular components. All authors contributed to the interpretation of the results, approved the final version of the manuscript, and agreed to be accountable for all aspects of the work.

Conflict of interest

There was no conflict of interest.

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