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Creating a Physical Sheep Head Surrogate from a Segmented CT Scan

by Christopher G. Sinks, Ian M. Berke, Louis J. Dankovich IV, Brian Fagan, Erika Matheis, and W. David Hairston

NOTICES

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14. ABSTRACT
Testing on live biological systems involves many processes and uncontrolled variables that can incur high costs and introduce undesired complexity into experimentation. Here, we develop a surrogate head device that allows for bench-level testing of bio-similar materials to reduce the need for live-animal experimentation. We take a segmented scan from a Dorper sheep and, through a combination of hydrogel chemistry and 3-D printing, create a multilayer head with embedded sensors to help confirm computational simulations of various conditions. While we still require significant iteration to fully reproduce every tissue type and geometry, we have created a base surrogate that has successfully been used in testing.

15. SUBJECT TERMS
Humans in Complex Systems, Tissue Surrogates, Tissue Phantoms, Tissue Simulant, 3D-Printing, Additive Manufacturing, Sheep Modeling, Hydrogels, Stereolithography, Fused Deposition Modeling

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1. Introduction

Biological systems are complex; understanding these systems is often done via simplified computational modeling. There is a large gap between a computational model of a biological system and the true functioning biology it is intended to represent. Confirming these models in vivo can require extensive sensing, expensive testing, and many iterations of animal experimentation, presenting significant challenges, both practical and ethical, in determining a biological system's response to a given stimulus. Surrogate devices, sometimes referred to as a "phantom," are typically used to bridge this gap. Phantoms are constructed from materials that imitate tissue on important parameters (mechanical, electrical, thermal, etc.) at an intermediate level of complexity necessary to confirm models' validity toward biological effects.

Here, we construct a first-generation surrogate of a Dorper sheep head derived from a live-animal CT scan and add pressure or temperature sensors so we can observe likely effects of electromagnetic radiation on animal subjects. Our computational modeling team provided a short list of design considerations and a segmented scan, and we produced a 3-D multilayer tissue surrogate simulating layers of brain, bone, bulk soft tissue, and skin.

2. Methods

2.1 Model Development and Printing Preparation

We were supplied with full-body scans of a Dorper sheep, segmented into skeleton and soft tissue. To develop a physical, 3-D model of this scan, the scan was first imported to Blender 4.2 (Blender 2024) and rendered as a 3-D computer model (Figure 1). All models are 1:1 scale with the original sheep. The model was then severed near the base of the C1 vertebrae to capture the anatomy relevant to the intended surrogate while also accommodating the dimensions of our in-house Formlabs 3BL, large-format stereolithography 3-D printer (Formlabs Inc., Somerville, Massachusetts). Detached geometry was removed, and to correct poorly constructed geometry, the model was remeshed at a 0.5 mm voxel size. The ears were deemed unnecessary by the computational modeling team for this experiment and omitted from the soft tissue model until a later iteration. Any resultant holes in the surface were filled in and contoured using filling and sculpting tools included in the Blender software. Figure 2 shows the first usable iteration of skull and soft tissue.

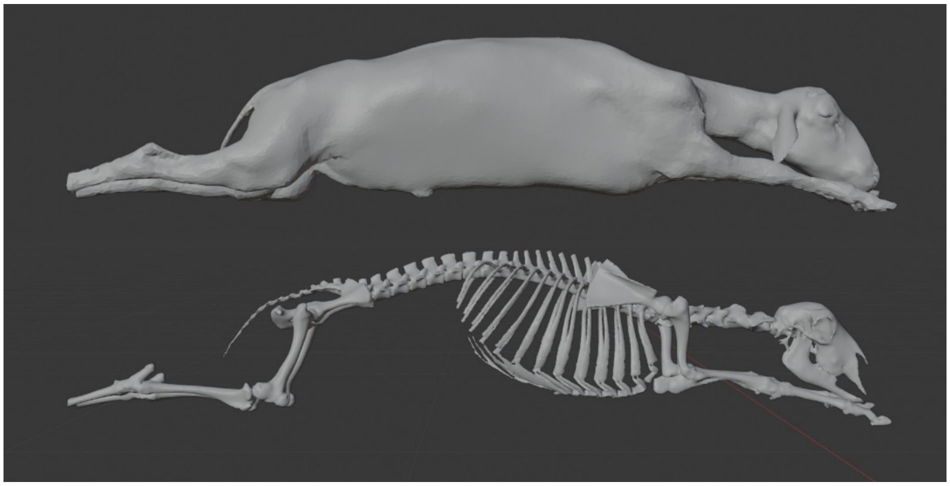

Figure 1. Original scans of the Dorper sheep.

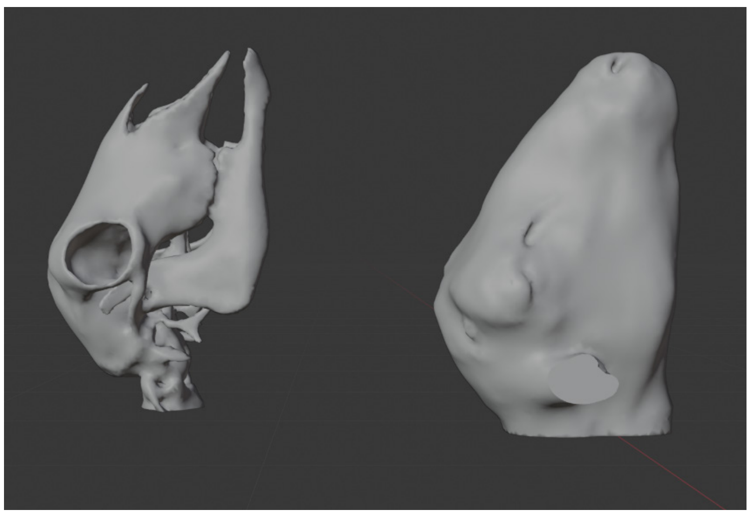

Figure 2. Skull and head extracted from the full sheep segmentation.

To supplement the head model, we required a base to orient, stabilize, and support the vertebrae and skull during casting, cooling, and testing. A drawing is included as Appendix A. The radius of the base was chosen to ensure it would support not only the skull print but also the eventual casting of the soft tissue material. A hole was centered where the spine meets the skull to allow casting of the soft tissue simulant in both the cranial cavity and outer soft tissue.

Two fiber-based sensing positions on the surrogate were requested—center of the forehead and center of the cranial cavity. The forehead position was accomplished by adding a series of C-shaped clips (Figure 3) to the base and skull; the soft tissue was sculpted in Blender to ensure full coverage of the clips. These clips allow a single fiber-based sensor to be placed on the forehead of the surrogate (Figure 4).

To center a sensor in the cranial cavity, we built a rigid cannula with an insert printed from Formlabs Elastic 50A (Formlabs Inc.; Somerville, Massachusetts) to hold the sensor in a specific position. This has a matching sleeve attached to the skull and allows for easy location of any desired sensor (Figure 5). This cannula and sleeve can be adapted to other sensors as necessary.

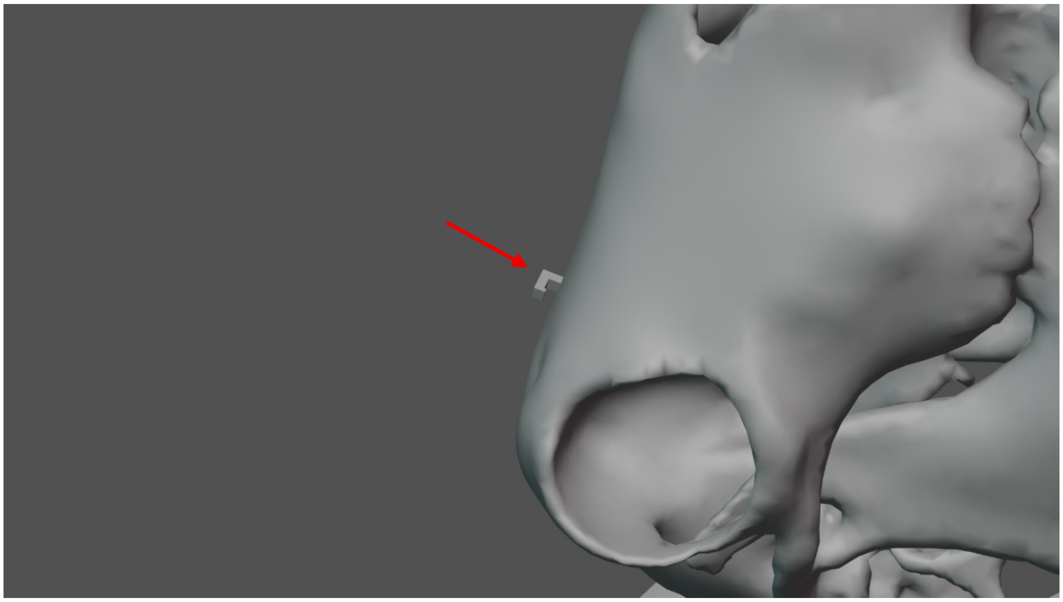

Figure 3. Close-up of the fiber clip on the forehead. (The large void in the bottom center of the image is the eye socket and the nose is pointed upward).

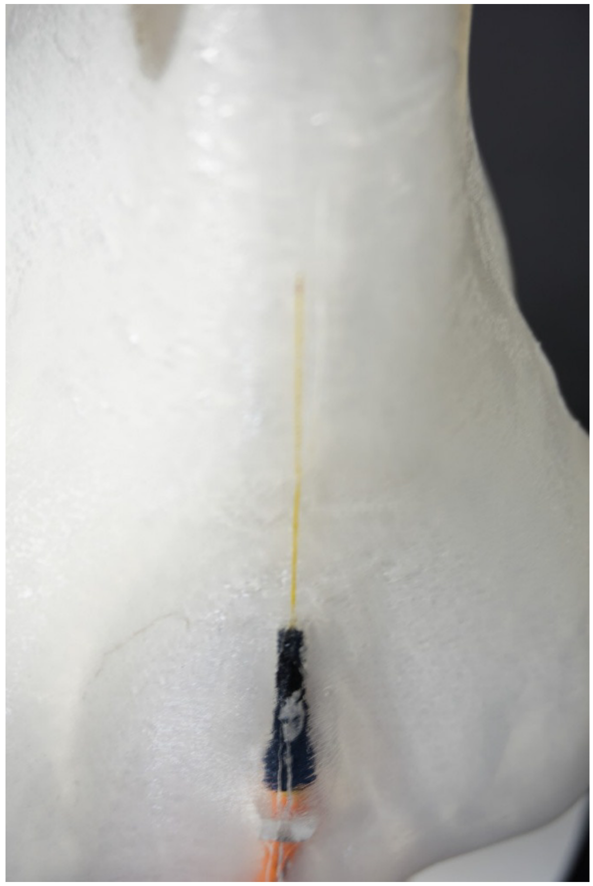

Figure 4. The temperature probe embedded in the forehead and clipped into a rostral, dorsal position. See Figure 9 for a full view.

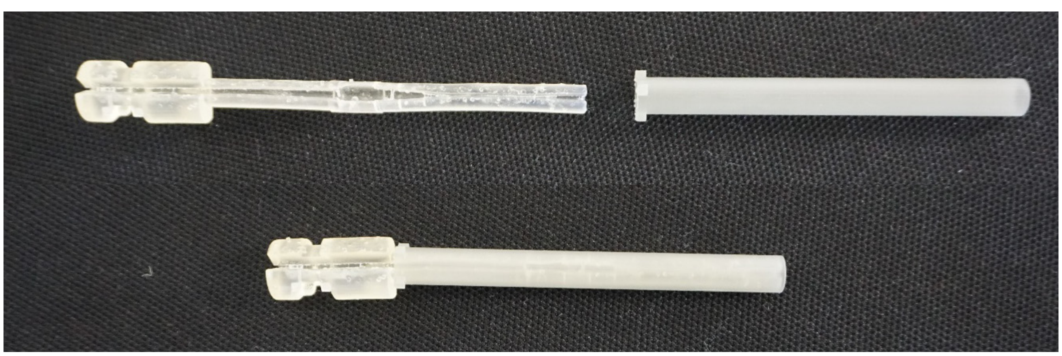

Figure 5. Probe cannula and elastomer insert; top: disassembled; bottom: assembled.

For the first generation, we built a case around the skull that created a void in the shape of the desired soft tissue. This was accomplished via a "shrinkwrap" modifier in Blender that allowed us to create a negative of a surface, followed by sculpting to accommodate otherwise sharp edges (e.g., the fiber clips). Lastly, the case was bisected to separate the halves across roughly the highest point along the skull to make the mold mostly concave and easier to release. Figure 6 is an exploded view of the full model.

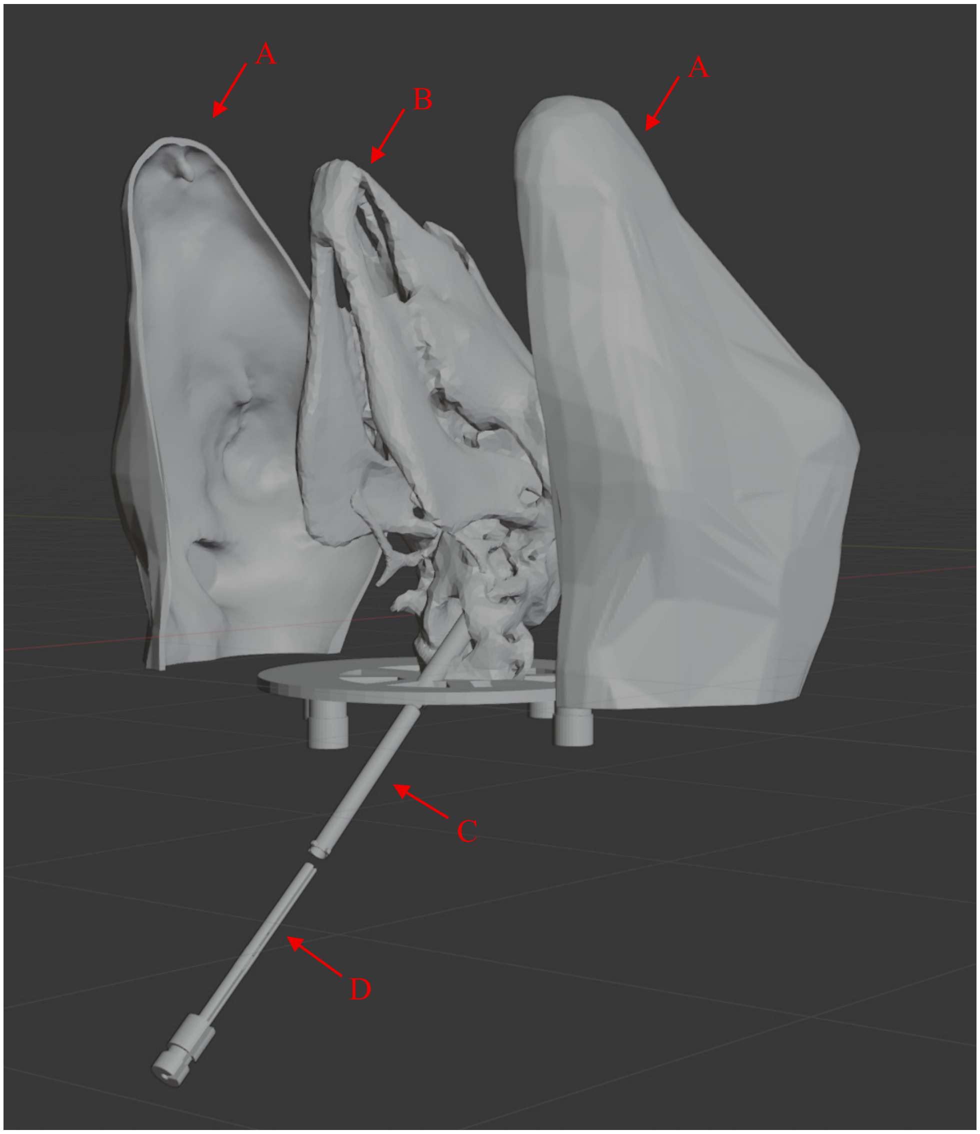

Figure 6. A) is the casting case, B) the main skull model, C) the cannula for sensors, and D) is a flexible guide to hold the specific temperature sensor in the cannula.

2.2 Printing Procedure

The skull, base, and fiber clips were assembled in Blender and exported to print on a Formlabs 3BL in Rigid 10k Resin (Technical Data Sheet [TDS], Appendix B) as it is a reasonable approximation of bone. This was set to print at 0.05 mm layer height over 2.5 days. The model was washed in 99% isopropyl alcohol for two 10-min cycles, then cured at 40 °C in a Form Cure L (Formlabs Inc.; Somerville, Massachusetts) for 1 h. We chose a lower-than-standard temperature for the cure, as the normal 60 °C was causing warping and sagging of the support base. Supports were left attached during the cure cycles to help combat warping. Supports were then carefully removed to ensure small features were left intact, and the outer surfaces were lightly sanded to remove support markings. Interior surfaces were sanded at friction fit spaces only.

The soft tissue case was printed from Bambu PPS-CF (carbon-fiber–reinforced polyphenylene sulfide) filament (TDS, Appendix C) on a Bambu Lab X1E printer (Bambu Labs; Shenzhen, China). No postprocessing was required. A thin layer of room-temperature-vulcanizing silicone was applied to the mating surface of the case, pressed together around the skull and attached sensors, and then secured with clamps and zip-ties. Figure 7 shows the skull inset in half of the case.

Figure 7. Half of the case around the skull.

We prepared Agarose RA (Avantor; Radnor, Pennsylvania) at 3.5% w/w in 70/30 w/w glycerol/deionized (DI) water with 1% w/w NaCl. Three identical 1-L batches were prepared in parallel, then combined in a 4-L beaker and degassed in an ultrasonic bath (Elmasonic P120H; Elma Schmidbauer Singen, Germany) at 80 ℃ for 15 min. Once fully clear, the agarose was poured into the mold, which was supported in a 2-L beaker. The beaker was filled with DI water, and the assembly was placed in the same ultrasonic bath on a degas setting with the heater shut off, allowing the assembly to cool from 80 ℃ to room temperature overnight and set. Small bubbles at the surface confirmed the release of small air pockets during cooling.

To confirm probe placement and gel permeation throughout the skull structure, we performed a CT scan of the finished surrogate. Sample slices are shown in Figure 8. Some small voids remain; however, the vast majority of the model perfused well, and the sensors are fully encapsulated in the agarose. Figure 9 shows four views of the completed head.

Figure 8. CT slice of the completed surrogate. Some small voids remain, but sensed areas are fully filled.

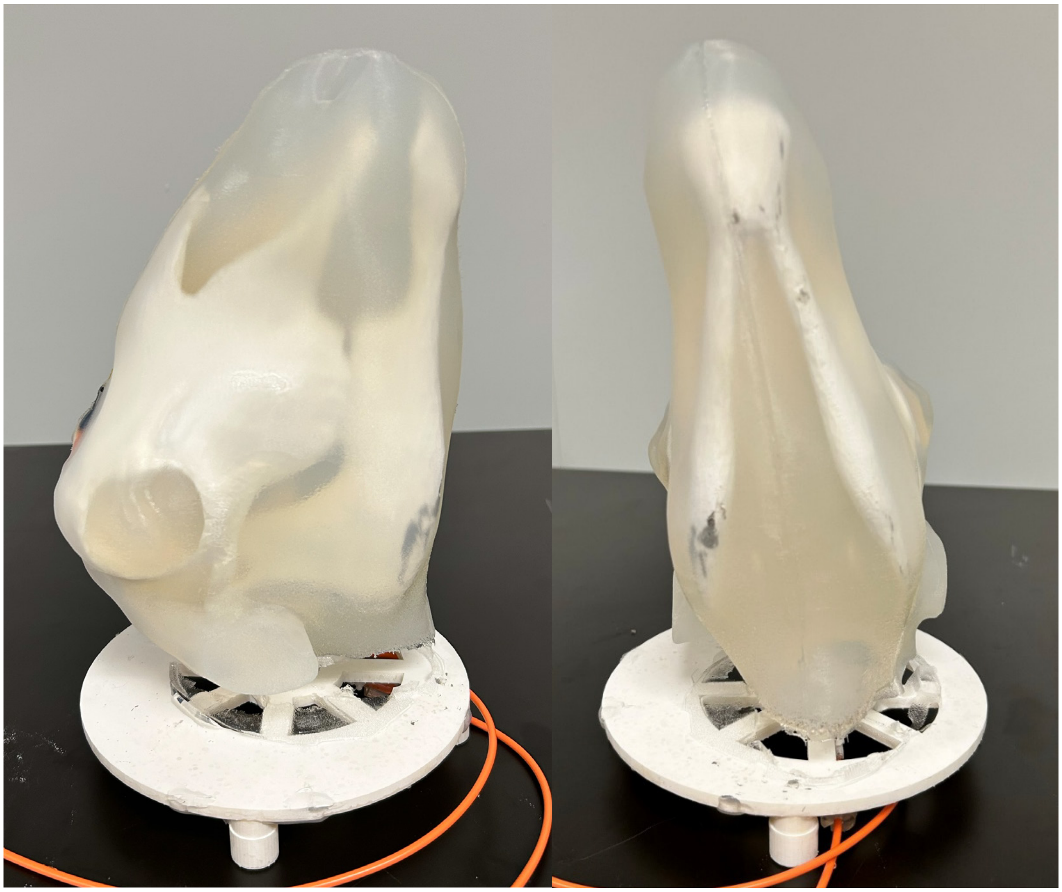

Figure 9. Full view of the completed sheep head surrogate.

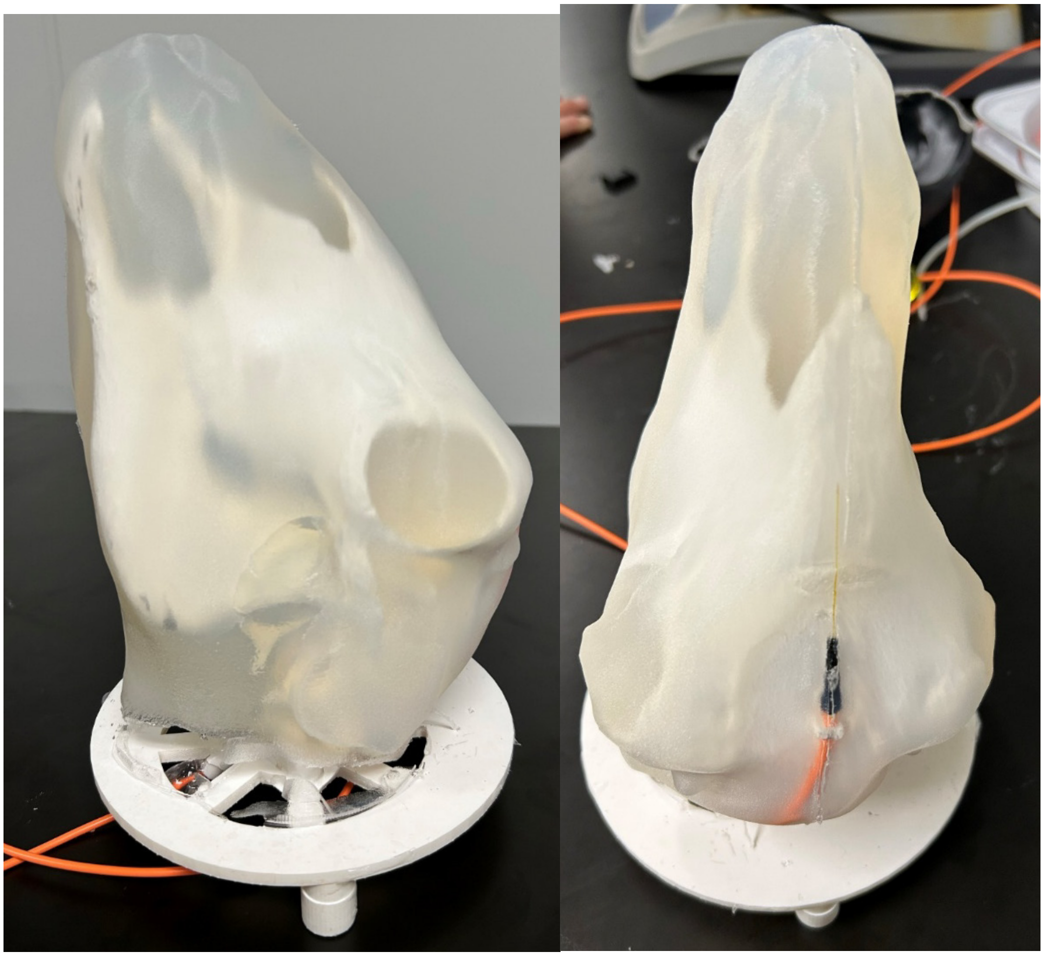

Figure 9. Full view of the completed sheep head surrogate (continued).

To validate the functionality of the surrogate, it was used in a mock thermal test. The surrogate was placed within the testing facility and allowed to equilibrate to the set ambient temperature (23.9 °C) for 2 h. This surrogate was cast with two embedded fiberoptic sensors (THR-NS-1463; FISO Technologies, Quebec, QC, Canada) to measure superficial skin and deep brain affiliated thermal fluctuations (Figures 10A, B). To measure skin surface and ambient thermal fluctuations, PRB-500 and PRB-242 probes were used, respectively (OSENSA; Burnaby, British Columbia, Canada). To reduce the influence of ambient heating, ventilation, and air conditioning (HVAC)-induced thermal fluctuations, the surrogate was placed within an insulated testing chamber (Figure 10C). Where appropriate, fibers were passed through a fiber feed port (Figure 10D) and mated with the FISO (SPC-HR) and OSENSA (FTX-300-LUX+) data acquisition systems. Data were acquired at greater than or equal to 2 Hz. Results highlight the influence of ambient thermal fluctuations, particularly at superficial locations (Figure 11); the deeply embedded sensor had minimal thermal fluctuation (<0.1 °C).

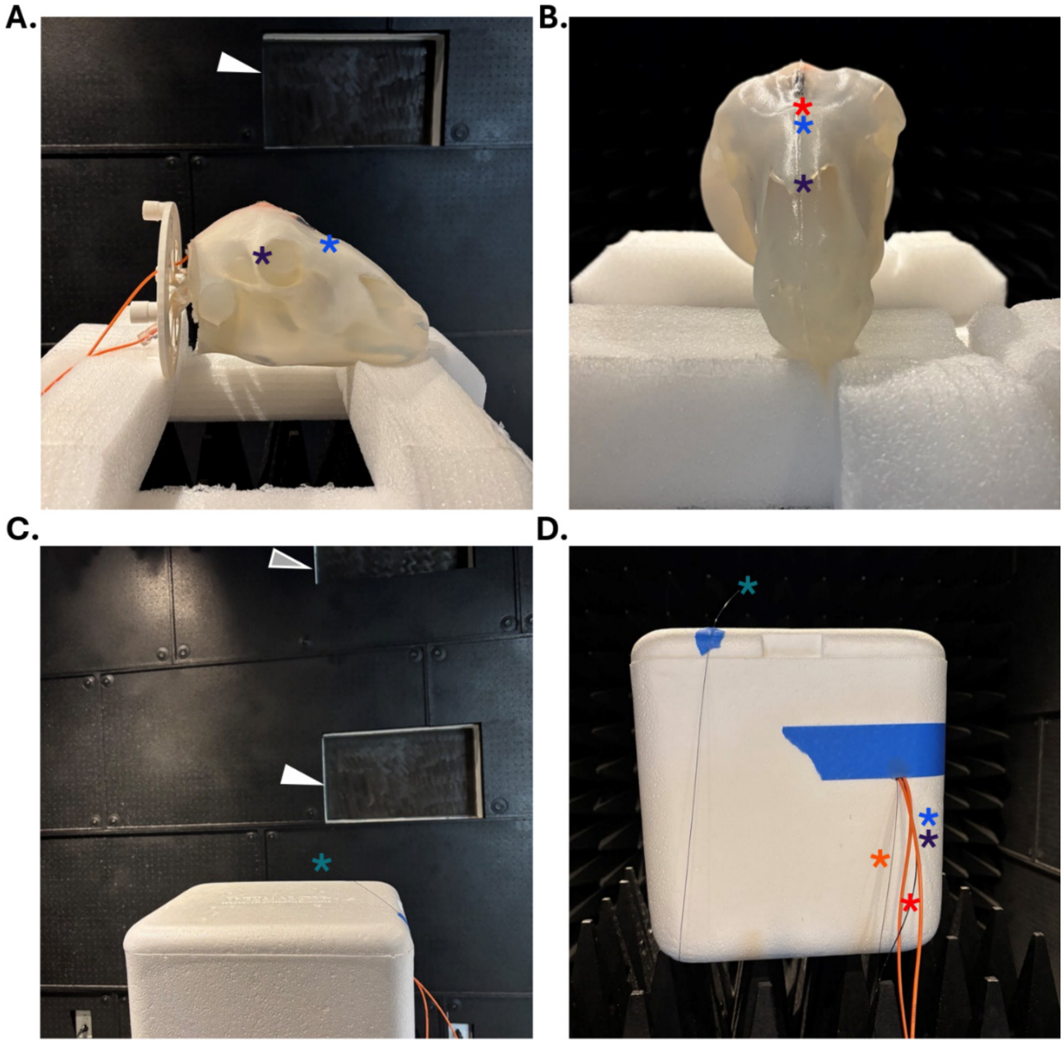

Figure 10. A) Coronal and B) sagittal plane views highlight the surrogate outside of the insulating test chamber. C) and D) show the surrogate within the insulated testing chamber along with embedded and affixed fiberoptic probes. White–gray carrots highlight HVAC inlet/outlets that influence test results. Color-coded stars highlight sensor and fiber locations: purple = brain embedded, blue = skin embedded, red = skin surface, orange = internal ambient, and green = external ambient.

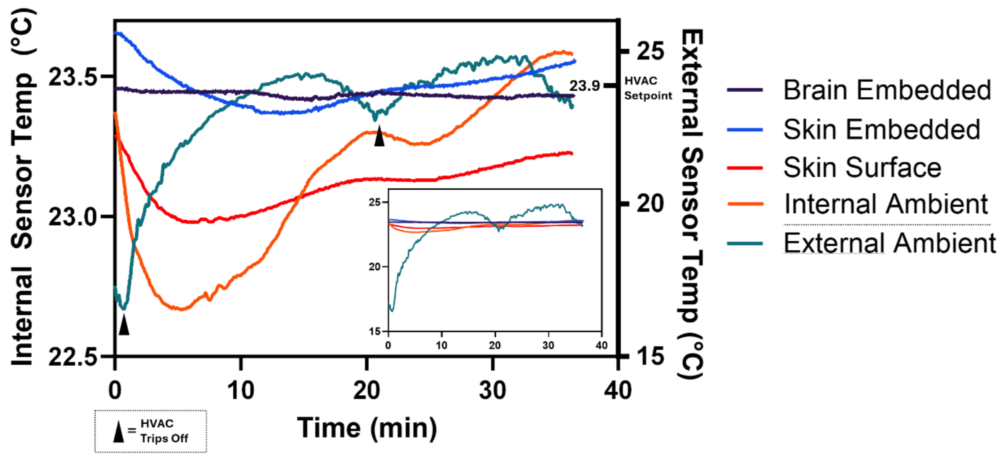

Figure 11. Thermal data can be simultaneously captured from upward of five probes simultaneously. Black carrots highlight when testing facility HVAC trips off, slow rises in the external ambient temperature can be observed (right axis). Simultaneously, this cycling can be observed to affect, to a lesser degree, probes within the insulated testing chamber (left axis). Within the inset, all data is plotted on one axis to illustrate the lagging thermal effects observed within the insulated testing chamber. Testing facility HVAC was set to maintain a temperature of 23.9 °C.

3. Conclusion and Future Work

We successfully created a multilayer, anatomically accurate surrogate sheep head as a tool for testing and model validation. While this head is embedded with temperature sensors for testing response to certain stimuli, the cannula and clips can be modified and used for any sensor that can tolerate the embedding process. The cannula can be varied in size, though this would require a reprint of the skull structure.

Some voids were noted within the skull structure upon CT. These can likely be resolved by preheating the skull and case to 80 °C and drawing a vacuum on the poured model. A lower temperature or free-radical-initiated soft tissue would allow more working time, and we are investigating other materials that both match soft tissue properties and improve working time.

Going forward, we intend to increase the complexity of the mold to retain more soft tissue features, including sinus voids and ears. We plan to create a full case that allows the unit to self-support during casting. We hope to segment different soft tissues to change material by tissue type to better match living tissue properties, with priority toward a simulated brain in the cranial cavity and more biofidelic skin. Now that we have successfully developed a process for manufacturing multilayer, biofidelic surrogate heads, we can now iterate on this design as necessary to further improve anatomical representation, biofidelity, and integrated instrumentation to support experimentation and future needs.

4. References

Blender. Version 4.2 [computer software]. Blender Studio; 2024. https://www.blender.org

Appendix A. CAD Drawing of Base and Probe Guide

The canula acts as a guide for the temperature sensor, protects the more delicate fiber optic components, and places it exactly where it needs to be in the center of the experimental volume. The canula's central channel is contoured to fit the probes exterior profile to hold it securely in place. A 20° wedge is cut out from the exterior to the center to allow the probe to be inserted. A flange near the top prevents over-insertion of the cannula and a channel cut into the flange allows application of a zip tie to add additional friction and pressure to further ensure the probe remains in a consistent location during experiments. The flange has a wedge cut from its bottom aspect that controls the angle of insertion into the experimental volume as a final control on placement. The skull base stand is shown in Figure A-1 and the probe guide in Figure A-2.

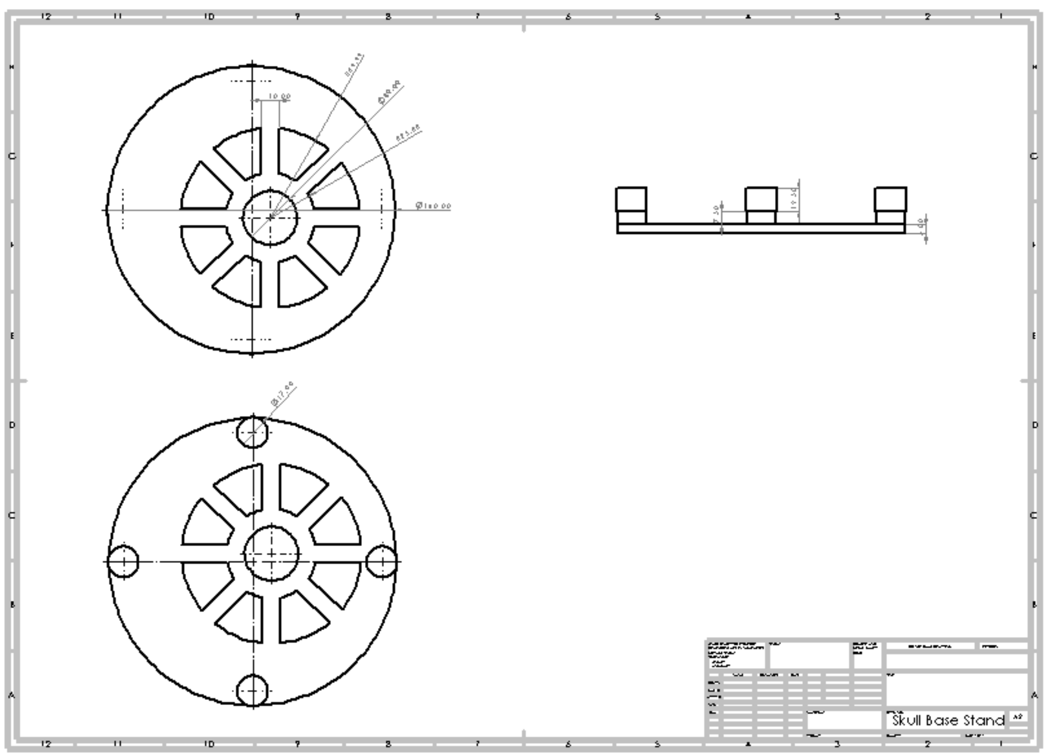

Figure A-1. Skull base stand.

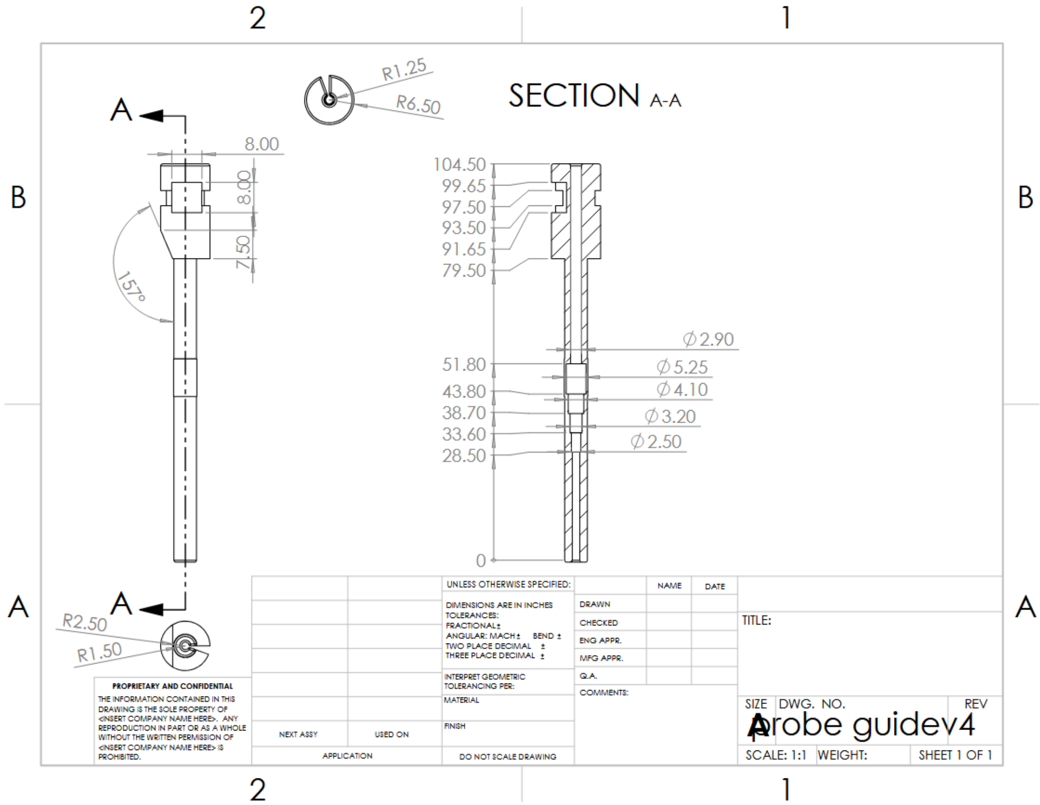

Figure A-2. Probe guide.

Appendix B. Rigid 10k Technical Data Sheet

This appendix appears in its original form as a PDF attachment.

Appendix C. PPS-CF Technical Data Sheet

This appendix appears in its original form as a PDF attachment.

List of Symbols, Abbreviations, and Acronyms

3-D	Three-Dimensional
ARL	Army Research Laboratory
CT	Computed Tomography
DEVCOM	U.S. Army Combat Capabilities Development Command
DI	Deionized
HVAC	Heating, Ventilation, and Air Conditioning
PPS-CF	Carbon-Fiber–Reinforced Polyphenylene Sulfide
TDS	Technical Data Sheet

1 (PDF)	DEFENSE TECHNICAL INFORMATION CTR DTIC OCA
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