

Mechanical Validation of a Patient-Derived Silicone Kidney Phantom for Nephroscope Access Testing

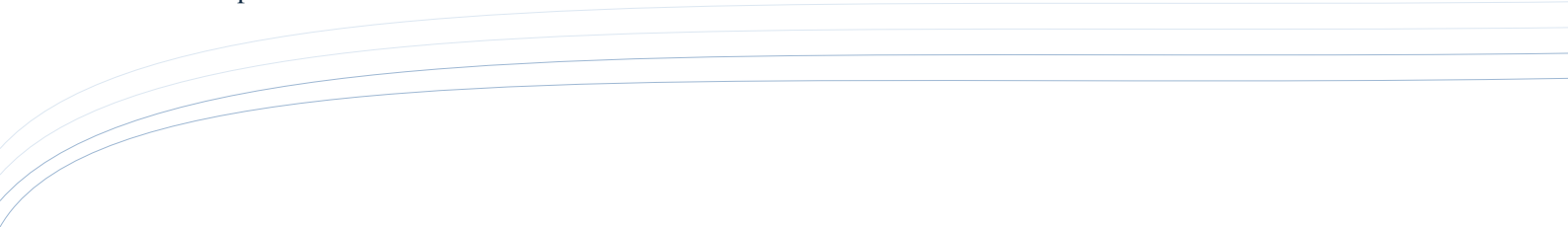
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Abstract

Percutaneous nephrolithotomy (PCNL) relies on a single percutaneous access tract chosen before the procedure, and the choice of access point is known to constrain which parts of the kidney's collecting system a surgeon can subsequently reach. This report describes the design, fabrication, and mechanical evaluation of a patient-derived silicone kidney phantom, built to test how percutaneous access-point choice affects calyceal reachability with a real nephroscope. The phantom's collecting-system geometry was sourced from a patient-derived model and cast in Ecoflex 00-30 silicone via a lost-core PVA technique; dimensional fidelity was validated against the source geometry both by discrete caliper measurement (mean relative error 0.73%, range 0–1.37%) and by full-surface photogrammetry comparison (mean signed offset 0.003 mm, standard deviation 0.52 mm), confirming close agreement outside of a few mechanistically explainable regions (mold seam, tracking markers, an intentional hilum simplification). Mechanical testing across the three standard percutaneous access points showed that access point clearly affected reachability: the lower pole access reached 8 of the phantom's 9 calyces, compared to 5 of 9 for the interpolar access and only 4 of 9 for the upper pole access, an asymmetry attributable to this patient's particularly open lower-pole anatomy rather than to trajectory alone. These results suggest that a CT-derived silicone phantom can reproduce sufficient geometric accuracy to serve as a validated navigation testbed for nephroscope development and PCNL training, without requiring cadaveric or animal tissue.

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1 Introduction

Percutaneous nephrolithotomy (PCNL) is the standard surgical technique for removing large kidney stones, and its success depends on the surgeon’s ability to navigate a rigid or semi-rigid nephroscope through the kidney’s internal collecting system — the network of cavities (calyces) that drain urine toward the ureter [1]. Unlike open surgery, PCNL relies on a single percutaneous access tract, chosen before the procedure, through which the entire operation is performed. The choice of this access point is a critical clinical decision: an access point that reaches the target stone easily from one location may make other calyces mechanically unreachable, and clinical comparisons of upper- versus lower-pole access report meaningful differences in the angles and trajectories available to reach the rest of the collecting system [2].

Despite the importance of this decision, most surgical trainees and engineers developing new nephroscope designs have limited tools to physically test how access-point choice affects reachability. Synthetic kidney phantoms, physical models that reproduce the internal geometry of the kidney’s collecting system, offer a way to test navigation mechanics repeatedly, safely, and without the ethical and logistical constraints of cadaveric or animal tissue. Prior work has used multi-access silicone kidney phantoms to study procedural variables in PCNL, such as renal pelvic pressure across patient positioning, with access sheaths fixed in the upper, middle, and lower poles [3], but mechanical reachability as a direct function of access-point choice has received less attention.

This report describes the design, fabrication, and preliminary mechanical evaluation of a silicone kidney phantom developed during a summer research internship at Dexterous Endoscopes, an EPFL spin-off working on next-generation nephroscope technology. No commercial phantom identified during supplier evaluation offered a collecting system large enough to meet the project’s initial validation tolerances, which motivated building a custom phantom rather than purchasing one. Unlike phantoms intended primarily for visual or training realism, this phantom prioritizes one property above all others: the geometric and dimensional fidelity of the internal collecting system, since this is what actually constrains a nephroscope’s mechanical navigation, achievable radius of curvature, deflection angle, and access to individual calyces.

The central research question addressed in this report is: *can a CT-derived silicone phantom reproduce sufficient geometric accuracy to serve as a validated navigation testbed, and does the choice of percutaneous access point determine which calyces a real nephroscope can subsequently reach?* Answering this required (1) building a phantom whose internal cavity geometry is derived directly from a real patient collecting system rather than idealized anatomy, (2) validating that geometry’s fidelity against the digital source both at discrete points and across the full surface, and (3) testing an actual nephroscope, on loan from Dexterous Endoscopes, inside that phantom under a fixed, repeatable protocol.



Figure 1: The final Ecoflex 00-30 kidney phantom.

2 Research Design

2.1 From patient anatomy to a physical model

The phantom’s internal geometry was based on a pre-existing 3D model of a human kidney, including its collecting system, obtained from Embodi3D, an online community platform where clinicians and researchers share 3D-printable anatomical models derived from real patient CT scans [4]. The source file, uploaded by user "Dr. Mike" and generated using Embodi3D’s democratiz3D conversion service, provided the kidney as a hollow shell with the collecting system cavity already present. Unlike simplified geometric approximations of the kidney, this patient-derived geometry preserves the irregular, branching structure of the collecting system, the feature that most affects navigation difficulty, and one that a hand-modeled or idealized kidney would not reproduce.

The downloaded model required cleanup before use: several small disconnected shapes on the exterior surface, apparent scan or reconstruction artifacts unrelated to the kidney’s actual anatomy, were identified and removed in Blender. To extract the collecting system as a printable solid part, a voxel remesh operation was applied to the cleaned hollow model to produce a solid ("filled") version of the kidney with no internal cavity. A Boolean difference between this solid version and the original hollow model then isolated exactly the cavity volume as a standalone printable solid, this became the geometry used for the PVA lost-core print. The outer mold enclosing this core (Section 2.2) was designed independently for this project.

The collecting system volume was segmented in Blender into individual minor calyces and grouped by approximate anatomical zone (upper, middle, lower; anterior, posterior) using vertex groups, to support both the calyceal accessibility trial (Section 3) and the corresponding visualizations. This extraction workflow, the calyceal segmentation, the mold design, and all casting and mechanical testing described below constitute the original contribution of this work; the underlying collecting system anatomy itself was sourced from the Embodi3D model.

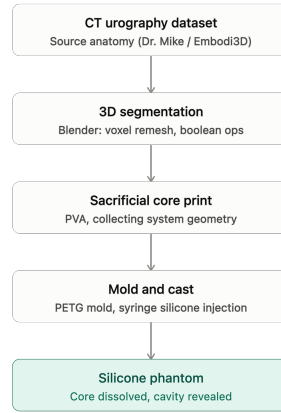


Figure 2: Fabrication pipeline from the Embodi3D hollow kidney model to the hollow silicone phantom: (1) source model with collecting system cavity [4], (2) voxel-remeshed solid version, (3) PVA core extracted via Boolean difference and printed, (4) cast & dissolved core revealing the final cavity network.

2.2 Fabrication: lost-core casting

The internal cavity geometry was reproduced using a lost-core casting method: the isolated cavity volume was 3D printed in polyvinyl alcohol (PVA), a water-soluble material, using a Bambu Lab H2D. This PVA core was then encased in a split PETG outer mold and silicone was cast around it. Once cured, the PVA core was dissolved in water, leaving a hollow cavity network with the exact geometry of the original patient’s collecting system.

The mold itself is a vertical, two-part design: a reservoir at the top was originally intended to feed silicone down through a channel to the bottom of the cavity, held together by alignment pins, M3 fasteners seated in hex-nut sockets, and finger-pull recesses to ease repeated demolding. The mold design went through two iterations. In the first version, silicone was poured from the top of the mold and expected to flow down into the cavity channel under its own weight, with a vent allowing air to escape. In practice, the silicone was too viscous to flow into the fine cavity geometry fast enough, and even actively drawing it upward by applying suction at the vent still left several unfilled voids in the final cast. The second version instead introduced an injection port at the bottom of the mold, allowing silicone to be injected upward through a tube and syringe directly into the cavity from below. This change fully resolved the incomplete-fill issue and was used for all subsequent casts.

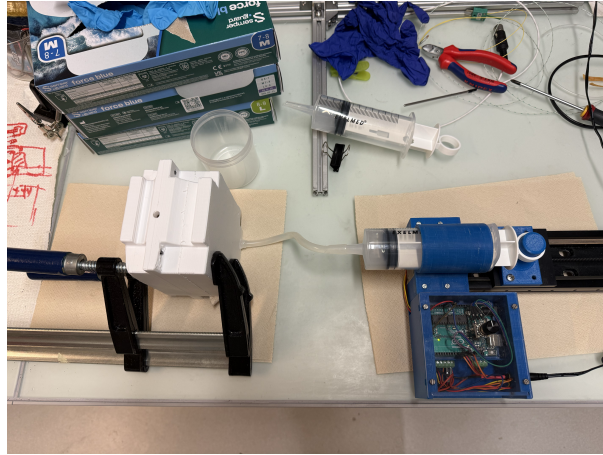


Figure 3: Setup for the casting of the silicone with the second iteration of the mold.

A geometric compromise was made near the renal hilum: the PVA core geometry in this region was locally simplified (material removed) to allow the two mold halves to be assembled, since the unmodified hilum geometry obstructed mold placement. This modification is a known, deliberate deviation from the source anatomy and is discussed in the context of the surface fidelity comparison in Section 3.4.

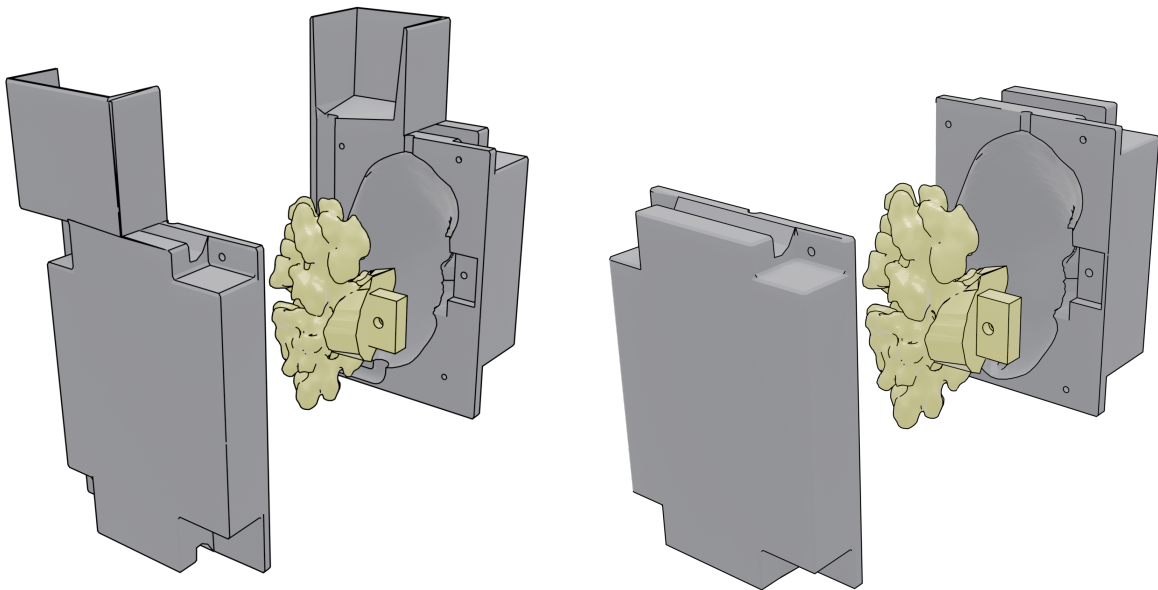


Figure 4: Mold design iteration. **Left (v1):** top-pour design with a vent, which under-filled the cavity despite suction assistance. **Right (v2):** bottom injection port allowing syringe-driven filling, which fully resolved the void issue.

2.3 Material selection

Three silicone formulations of differing hardness were cast: Dragon Skin 30 (Shore A30), Dragon Skin 20 (Shore A20), and Ecoflex 00-30 (Shore 00-30, a much softer scale than the Shore A used for the other two). Ecoflex 00-30 was selected as the primary material for mechanical testing based on prior work on soft, anatomically realistic kidney phantoms, which used soft materials in a comparable stiffness range to approximate real kidney tissue for endoscopy and mechanical testing purposes [5]. Dragon Skin 30 and 20 were cast for material screening but were not carried forward into the mechanical access trial, as their stiffness was judged too far from target renal tissue stiffness for the navigation test to be representative.

2.4 Mechanical access protocol

To evaluate how access-point choice affects calyx reachability, a real nephroscope (on loan from Dexterous Endoscopes) was inserted into the Ecoflex 00-30 phantom through three percutaneous access points, corresponding to standard clinical access sites: upper pole, interpolar (mid-pole), and lower pole [2, 3]. Each access point was simulated using a rigid PVA-printed cylindrical insert mimicking an Amplatz sheath, placed directly into the phantom at the corresponding site; no surrounding torso model (ribs, skin thickness, pleura, or other organs) was used, so this protocol isolates intrarenal navigation and reachability only, and does not capture the external anatomical constraints (e.g., rib crossing, pleural injury risk) that inform access-point choice clinically.

Each individual calyx of the collecting system (nine in total) was marked with a visible dot prior to testing (Figure 5). For each of the three access points, a calyx was considered reached if its dot could be directly observed on the endoscope monitor from a reasonable viewing distance. A calyx reached on the first attempt was classified as *easy*; if not, up to two repositioning attempts were permitted, and a calyx reached within these was classified as *difficult*. This binary-then-graded criterion was chosen over a continuous scoring scale to keep the assessment simple and easy to verify from recorded footage. All trials were conducted by the author with a supervisor present.

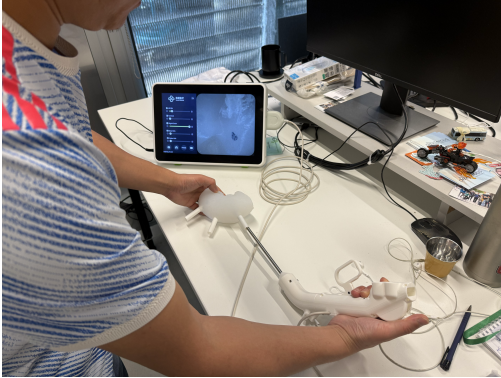


Figure 5: Test setup: the nephroscope inserted through a PVA sheath simulating one of the three percutaneous access points, with a supervisor present throughout testing (left), and a marked calyx as viewed on the monitor, used as the reachability criterion (right).

3 Analysis and Findings

3.1 Reachability by access point

Access point clearly affected reachability: the lower pole access reached 8 of the 9 calyces (5 easily, 3 with repositioning), compared to 5 of 9 for the interpolar access and only 4 of 9 for the upper pole access. No calyx was entirely unreachable from every access point, each of the 9 calyces was reached, at least with repositioning, by at least one of the three access points, but the upper pole access in particular left 5 of 9 calyces unreached. This asymmetry runs counter to the intuition, discussed in the Introduction, that upper pole access can offer a straighter trajectory along the kidney’s long axis; two factors specific to this patient-derived geometry

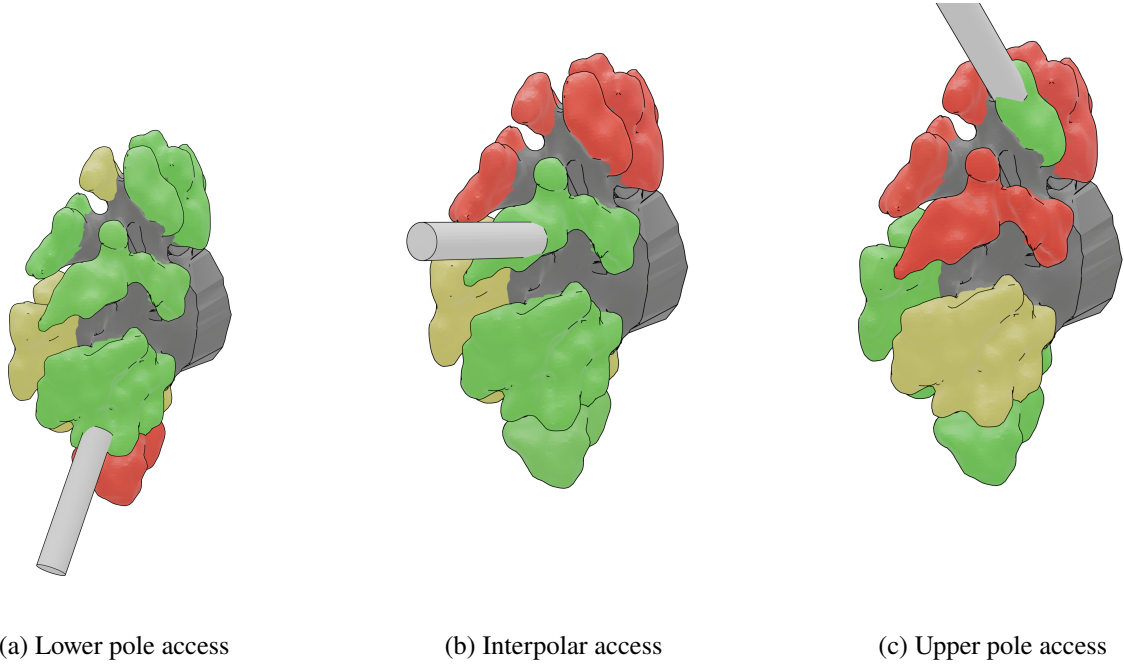


Figure 6: Calyceal reachability by percutaneous access point. Each calyx is colored by whether its marker dot was directly observable on the monitor from that access point (green: easy, first attempt; yellow: difficult, reached within two repositioning attempts; red: not reached).

Table 1: Calyceal reachability by percutaneous access point, out of 9 calyces total.

Access point	Reached easily	Reached with repositioning	Total reached	Not reached
Upper pole	3	1	4	5
Interpolar	3	2	5	4
Lower pole	5	3	8	1

likely explain it instead. First, the lower pole region of this particular collecting system is substantially more open, with larger and better-connected calyces, while the upper pole has a cluster of smaller, more tightly folded calyces, a patient-specific anatomical feature rather than a general property of upper-pole trajectories. Second, because access points were simulated with a fixed PVA sheath and no surrounding torso model, this comparison captures only intrarenal geometric reachability; it does not weigh the external, clinically important trade-offs of upper pole access (e.g., pleural injury risk, discussed in the Introduction) that would factor into a real access-point decision.

3.2 Qualitative observations

The main obstruction encountered was near the upper pole, where a cluster of small calyces created folded silicone surfaces and tight entry points; this was compounded by the absence of any lubrication or irrigation fluid during testing, which made the silicone surface noticeably tacky against the nephroscope. In a real PCNL procedure the continuous irrigation flow used to maintain visibility would also lubricate the tract, so this is expected to overstate the difficulty of the tightest passages relative to clinical conditions. Some calyces were only reached after several repositioning attempts; whether this reflects a genuine widening of the silicone tract from repeated passage, or simply the operator finding a better angle through trial and error, could not be distinguished with the current protocol. All trials were conducted by the author with a supervisor present throughout testing (Figure 5).

3.3 Dimensional fidelity

Six external dimensions were compared between the CT-derived Blender model and the physical Ecoflex 00-30 cast, measured with a manual caliper: total length, hilum-region thickness, maximum width of the upper and lower hilum halves, and height from the hilum to the superior and inferior poles.

Table 2: External dimensional comparison between the CT-derived model and the physical silicone cast.

Dimension	CT model (mm)	Physical cast (mm)	Relative error
Total length	142.0	141.0	0.70%
Hilum thickness	66.9	66.7	0.30%
Upper hilum half, max width	75.0	74.0	1.33%
Lower hilum half, max width	64.3	64.3	0.00%
Hilum-to-superior-pole height	57.3	56.9	0.70%
Hilum-to-inferior-pole height	58.6	57.8	1.37%

Across all six dimensions, the mean relative error was 0.73% (range: 0–1.37%), indicating close dimensional agreement between the digital model and the physical cast. Notably, the physical cast was smaller than or equal to the CT-derived model on every single dimension measured, with no cases of over-sizing. This consistent directionality suggests a systematic effect rather than random measurement noise, and is consistent with two non-exclusive explanations: (i) compression of the soft silicone surface under caliper jaw pressure during measurement, which would bias physical readings downward regardless of the true cast dimensions, and (ii) genuine shrinkage introduced during casting or PVA/PETG print tolerances.

3.4 Full-surface fidelity via photogrammetry scan comparison

To complement the six discrete caliper measurements above with a non-contact, full-surface assessment, the physical cast was digitized by photogrammetry (KIRI Engine) and compared to the CT-derived reference model across its entire external surface, rather than at a small number of discrete points.

3.4.1 Method

The photogrammetry-derived scan mesh (hereafter scan) was compared against the mesh of the kidney with the renal collecting system, since the voxel-remeshed version induces only negligible modifications of the external surface. The drawback of using the kidney model with the collecting system is that it introduces new errors on the internal surfaces, restricting the plots produced by CloudCompare to a qualitative analysis. The scan was rescaled in Blender using an A4 sheet of paper placed in-frame as a reference length. Both meshes were exported from Blender and registered in CloudCompare (v.2.14 beta) using an Iterative Closest Point (ICP) fine registration, without permitting further scale adjustment since the rescaling had already been done. Signed cloud-to-mesh (C2M) distances were then computed at every point of the scan relative to the reference surface, with positive values indicating excess material (scan surface outside the reference) and negative values indicating a deficit (scan surface inside the reference).

3.4.2 Results

Preliminary results (rigid registration) gave a mean signed distance of 0.003 mm with a standard deviation of approximately 0.52 mm across the full surface, an essentially neutral offset, tighter than the discrete caliper comparison above. Visual inspection of the resulting heatmap (Figure 7) showed the surface to be predominantly near-neutral (small, spatially diffuse deviations rather than large uniform offsets), with three categories of localized departure from this baseline:

- **Negative deviation (deficit) near the mold parting line.** Consistent with a small gap or incomplete fusion of silicone at the seam between the two mold halves.

- **Positive deviation (excess) far from the seam.** This is caused by some small bulging of the mold after the injection of the silicone.
- **Positive deviation (excess) at the renal hilum.** This coincides with the region where the PVA core geometry was deliberately simplified to permit mold assembly (Section 2.2). This is an intentional design compromise rather than a fabrication defect, and is treated separately from the aggregate error statistics above.

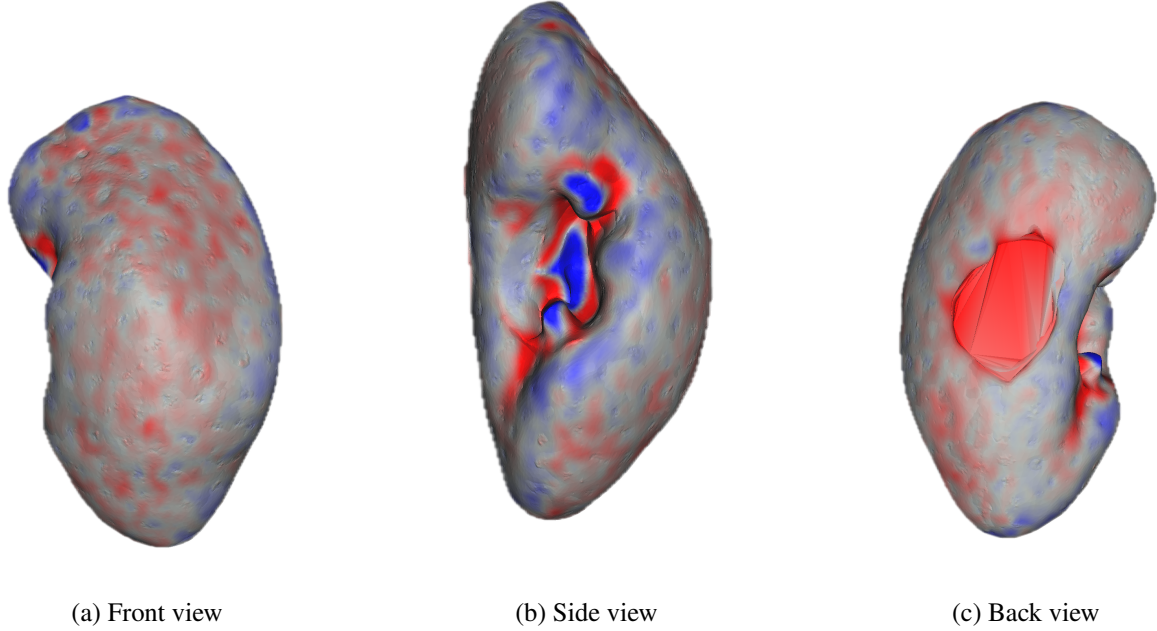


Figure 7: Signed cloud-to-mesh distance between the photogrammetry scan of the physical cast and the CT-derived reference surface. Blue: scan surface inset relative to reference (deficit); grey: near-zero deviation; red: scan surface proud of reference (excess).

Taken together with the caliper-based comparison in Section 3.3, the full-surface scan supports the same overall conclusion, close dimensional agreement between the digital model and the physical cast, on the order of a fraction of a millimeter to roughly a millimeter, while additionally localizing the largest departures to specific, mechanistically explainable regions (mold seam, marker placement, deliberate hilum simplification) rather than a diffuse, unexplained error across the whole surface.

4 Conclusion

This report set out to answer two linked questions: whether a CT-derived silicone phantom can reproduce sufficient geometric accuracy to serve as a validated navigation testbed, and whether the choice of percutaneous access point determines which calyces a real nephroscope can subsequently reach. On the first question, the evidence is strong: discrete caliper measurements showed a mean relative error of 0.73% against the source geometry, and an independent full-surface photogrammetry comparison found an essentially neutral mean offset (0.003 mm) with a tight spread (0.52 mm standard deviation), with the largest localized departures traceable to specific, explainable causes (the mold seam, tracking markers, and a deliberate hilum simplification) rather than to unexplained fabrication error. On the second question, access point clearly mattered: the lower pole access reached 8 of the phantom’s 9 calyces, compared to 5 of 9 for the interpolar access and only 4 of 9 for the upper pole access. Every calyx was reachable from at least one access point, but none of the three access points alone gave full coverage, most notably, the upper pole access left more than half of the calyces unreachable. This pattern is best explained by a patient-specific anatomical feature of the source geometry (a markedly more open lower pole) rather than a general property of access-point trajectories, and reinforces the value of testing against real, irregular anatomy rather than an idealized collecting system.

These findings have two practical implications. First, for nephroscope development, a patient-derived silicone phantom validated to sub-millimeter accuracy offers a repeatable, low-cost bench test for mechanical navigation, diameter and deflection requirements can be checked against a specific, known geometry rather than an idealized one. Second, for PCNL training and access-site planning, the results are a concrete reminder that no single access point can be assumed to give full coverage of the collecting system, and that the best access point is likely to be patient-specific rather than a fixed rule of thumb; a phantom built from a given patient's own anatomy could, in principle, be used to rehearse and compare access strategies before the real procedure.

This work has several limitations worth stating explicitly. The phantom reproduces the anatomy of a single patient's collecting system; the reachability pattern observed here is specific to that anatomy and should not be generalized as a rule about upper, interpolar, or lower pole access in general. Access points were simulated using PVA sheaths placed directly into the phantom without a surrounding torso model, so this protocol captures intrarenal reachability only and does not weigh the external, clinically important factors (such as pleural injury risk for upper pole access) that inform real access-point selection. No lubrication or irrigation fluid was used during testing, which likely overstated the difficulty of the tightest passages, particularly near the upper pole, relative to clinical conditions where continuous irrigation is present. The remaining directional bias in the caliper measurements (physical cast consistently smaller or equal, never larger) was not fully resolved to a single cause within the scope of this internship, and would benefit from a low-contact-pressure remeasurement to isolate caliper compression from genuine shrinkage. Finally, each access-target combination was attempted at most three times (one direct attempt plus up to two repositioning attempts), which is enough to classify reachability but not enough to draw firm conclusions about whether repeated passage genuinely widens the tract or whether later successes simply reflect improved operator technique.

Concrete next steps include: repeating the access trial with irrigation fluid to better approximate clinical conditions; extending the dimensional and reachability validation to additional patient-derived geometries to test whether the lower-pole advantage observed here generalizes or is specific to this anatomy; resolving the outstanding Embodi3D licensing question for the source model before any public release of derived figures or files; and, if the mold's licensing situation permits, sharing the mold and core design files to allow other labs to reproduce and validate the phantom independently.

References

- [1] Jean de la Rosette, Dean Assimos, Mahesh Desai, Jorge Gutierrez, James Lingeman, Roberto Scarpa, and Ahmet Tefekli. The clinical research office of the endourological society percutaneous nephrolithotomy global study: indications, complications, and outcomes in 5803 patients. *Journal of Endourology*, 25(1): 11–17, 2011. doi: 10.1089/end.2010.0424.
- [2] American Urological Association. Upper vs lower pole percutaneous renal access. AUA News, June 2024. URL <https://auanews.net/issues/articles/2024/june-extra-2024/upper-vs-lower-pole-percutaneous-renal-access>.
- [3] Ala'a Farkouh, Kyu Park, Matthew I. Buell, Nicole Mack, Cliff De Guzman, Toby Clark, Elizabeth A. Baldwin, Kanha Shete, Rose Leu, Akin S. Amasyali, Evan Seibly, Kai Wen Cheng, Sikai Song, Zhamshid Okhunov, and D. Duane Baldwin. Prone vs supine percutaneous nephrolithotomy: does position affect renal pelvic pressures? *Urolithiasis*, 52:41, 2024. doi: 10.1007/s00240-024-01555-6.
- [4] Dr. Mike. Left kidney stl file. 2018. URL <https://www.embodi3d.com/files/file/6666-left-kidney-stl-file/>. Generated using the democratiz3D conversion service from a CT scan. NOTE TO SELF: log in to confirm exact upload date and any usage terms beyond the listed license before public release.
- [5] Fabian Adams, Tian Qiu, Andrew Mark, Benjamin Fritz, Lena Kramer, Daniel Schlager, Ulrich Wetterauer, Arkadiusz Miernik, and Peer Fischer. Soft 3d-printed phantom of the human kidney with collecting system. *Annals of Biomedical Engineering*, 45(4):963–972, 2017. doi: 10.1007/s10439-016-1757-5.