Supplemental Figure Legends

Supplemental Figure 1. Meshmixer basics, terminology, software downloading guide, and helpful links

Supplemental Figure 2. Meshmixer procedural steps to design and generate NAMs. Each step is outlined with individual commands to perform iterative design modifications and generation of prosthesis. These include Step 1: STL file import into Meshmixer, Step 2: Orienting and preparing the model for further processing, Step 3: Model preparation including assessing and eliminating voids, trimming models, removing artifacts, Step 4: Identifying and blocking out the cleft areas, Step 5: Fabricating the prosthesis for basal seat, peripheral seating and seal, adjusting base thickness, smoothening surfaces and margins, Step 5: Adding prosthesis accessories like retention button and ventilation hole, and Step 6: preparing printing file (STL), slicing (GCode), and SLA 3D printing the prosthesis.

Supplemental Figure 3. Procedural steps to assess feasibility and accuracy of Cloud Compare software for spatial discrepancy that includes surface deviation analysis involving importing, registration, and alignment followed by statistical analysis and visualization using a heat map.

Supplemental Figure 4. Calibration exercise to verify the CloudCompare process using a standard object

Supplemental Figure 1.

Meshmixer Basics

Meshmixer is a free, lightweight yet powerful 3D mesh-editing toolkit developed by Autodesk. It's ideal for the final stages of 3D workflows - cleaning scans, sculpting, hollowing, generating supports, and preparing for printing - particularly for dental appliances like NAM. Meshmixer excels at direct surface manipulation, repair, and optimization of triangle-based models.

Autodesk's final official build - version 3.5.474, released on January 6, 2025 - is available for Windows (64-bit) (~113 MB) and macOS (universal) (~92 MB).

Terminology

A mesh in 3D graphics refers to a surface representation composed of polygons - most commonly triangles in a triangle mesh. These triangles are connected at edges and vertices to form a continuous surface suitable for manipulation and printing.

The Standard Triangulation Language (STL) file format encodes the surface geometry of 3D objects via a collection of triangular facets, collectively known as a mesh. Each triangle in the mesh defines a small portion of the surface, enabling detailed yet lightweight digital representation of anatomical models.

Triangulation is the process of subdividing a surface into triangles (or a planar domain into triangles) such that they meet edge-to-edge and vertex-to-vertex. It is fundamental to mesh representation because triangles are universally manageable by graphics pipelines and ensure consistent rendering, editing, and export behavior across tools. The process of triangulation ensures compatibility across 3D modeling and printing platforms, including Meshmixer.

User Guidance – A Note to Clinicians: For clinicians or researchers unfamiliar with 3D design software, it is normal to experience a learning curve when first using Meshmixer. While the interface may initially appear complex, repeated use and step-by-step practice will build familiarity. Patience is encouraged - Meshmixer's flexibility and control can offer precise, highly customized appliance design once mastered. Meshmixer remains reliable for both personal and commercial use, though active development has ceased - users should prefer official sources or well-trusted archives when downloading.

Helpful Links:

- Autodesk Meshmixer website: https://help.autodesk.com/view/MSHMXR/2019/ENU/
- Overview of tools: https://help.autodesk.com/view/MSHMXR/2019/ENU/?guid=GUID-9B48D29A-C62F-4E13-8AB4-54E19F1F9875
- Meshmixer Forum: https://forums.autodesk.com/t5/meshmixer-forum/bd-p/meshmixer-forum-en

Supplemental Figure 2.

Step 1: STL File & Meshmixer Software Acquisition

The experimental digital workflow began by digitizing identical gypsum maxillary casts using a desktop 3D scanner (3Shape E4). This process generated high-resolution 3D surface models in the Standard Tessellation Language (STL) format, with a spatial resolution of 50 micrometers. These STL datasets were subsequently imported into open-source 3D modeling software - **Meshmixer** (Autodesk) - for virtual appliance design and modification.

Meshmixer (Autodesk Research) is freely available and supported on Windows platforms. The software offers a suite of mesh-editing tools ideal for the design and modification of medical or dental appliances such as nasoalveolar molding (NAM) devices.

How to Download and Install Meshmixer (Windows & macOS)

Follow this step-by-step guide to obtain Meshmixer and prepare your system for the digital workflow:

For Windows (10/11, 64-bit)

1. Download the Windows 64-bit installer (version 3.5.474, ~113 MB) directly from Autodesk's official release.meshmixer.org
2. Verify the digital signature: Right-click the .exe → Properties → *Digital Signatures* tab, ensuring it's signed by Autodesk.meshmixer.org
3. Run the installer (UAC may ask for permission—choose Yes).
4. Accept license terms and install to the default folder (e.g., C:\Program Files\Autodesk\).
5. Optionally, disable telemetry in installer settings for a more private install.
6. Click Finish to launch Meshmixer.

For macOS (Intel or Apple Silicon)

1. Download the macOS version (~92 MB, universal build).meshmixer.org
2. Open the .dmg installer and drag Meshmixer.app into your Applications folder.
3. On first launch, macOS Gatekeeper may block execution—go to System Settings → Privacy & Security → click Open Anyway, then relaunch.meshmixer.org
4. If running on Apple Silicon (M1/M2/M3), macOS will prompt installation of Rosetta 2—accept to enable compatibility.

Note: This workflow is demonstrated using the default Meshmixer settings immediately following installation. Users are advised not to alter preference settings unless otherwise instructed in subsequent steps.

Step 2: Model Orientation and Preparation

Initial Positioning in Meshmixer

After importing the STL file into Meshmixer, use the Transform tool to center and orient the model within the 3D scene:

1. Navigate to the Edit menu → select Transform.
2. Use the on-screen translation and rotation handles to reposition the model.
3. Align the model such that it is symmetrically centered around the red origin point, which denotes the center of the Meshmixer coordinate system.

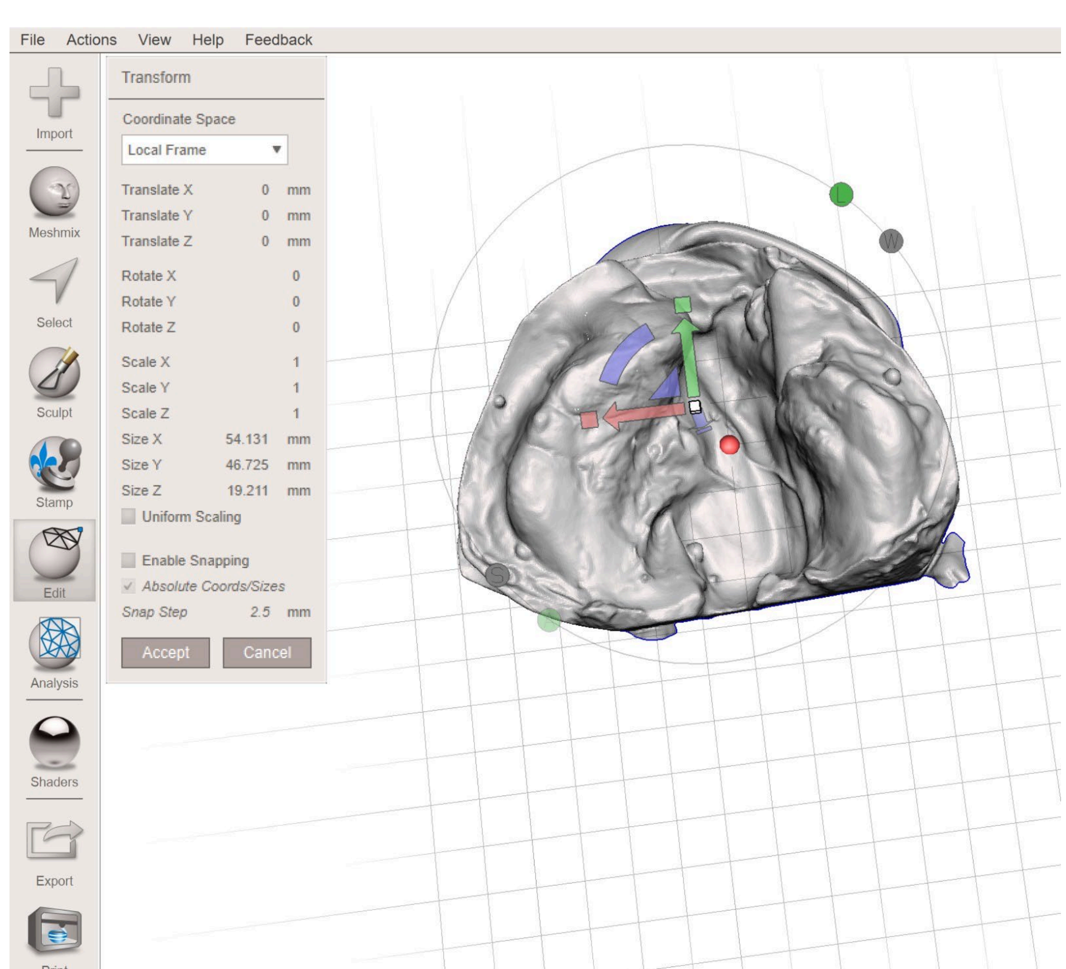
Note: The red point at the center of the scene is a useful reference for orientation—it defines the origin (0,0,0) of the digital workspace.

Establishing Proper Orientation for Appliance Design

Each maxillary cast was oriented to reflect a clinically appropriate path of insertion (POI) for the future NAM appliance. This orientation ensured:

1. Visibility of palatal margins critical for appliance adaptation.
2. Identification of anatomical undercuts (e.g., alveolar ridges, cleft margins) that may interfere with appliance placement or removal.
3. Appropriate axis alignment to facilitate downstream sculpting, trimming, and appliance modeling in subsequent steps.

Clinical Note: Proper model orientation is critical. Incorrect positioning can lead to appliances that do not seat fully or that engage excessive undercuts, compromising both retention and patient comfort.



Supplemental Figure 2. (*Continued*)

Step 3: Model Mesh Cleanup

Due to the physical origin of the data (i.e., digitized gypsum cast models), the STL files often contained surface imperfections such as voids, bubbles, unwanted scan areas, or extraneous geometry. For users working with intraoral scans, this step may be optional, as such datasets typically lack casting-related artifacts.

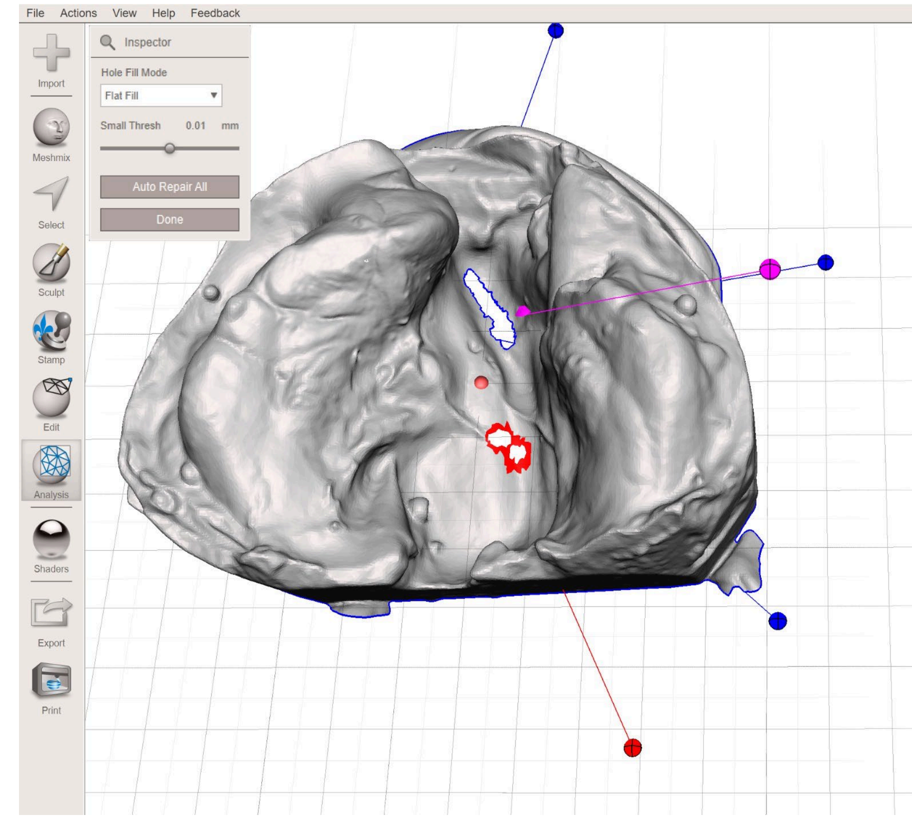
Systematic mesh refinement was performed to ensure a clean, printable model suitable for digital appliance design.

A. Void Inspection and Mesh Repair

Mesh integrity was evaluated and corrected using Meshmixer's built-in diagnostic tools:

1. Navigate to the main toolbar: Analysis → Inspector
2. Meshmixer automatically highlights defects using a color-coded system:
    - Violet – Floating or disconnected mesh surface
    - Blue – Simple hole in the mesh
    - Red – Complex or irregular hole in the mesh
3. To repair:
    1. Click on individual defects for manual correction
    2. Or select "Auto Repair All" to resolve all issues automatically

Tip: After automatic repairs, inspect the model to ensure no critical anatomical features were unintentionally modified.

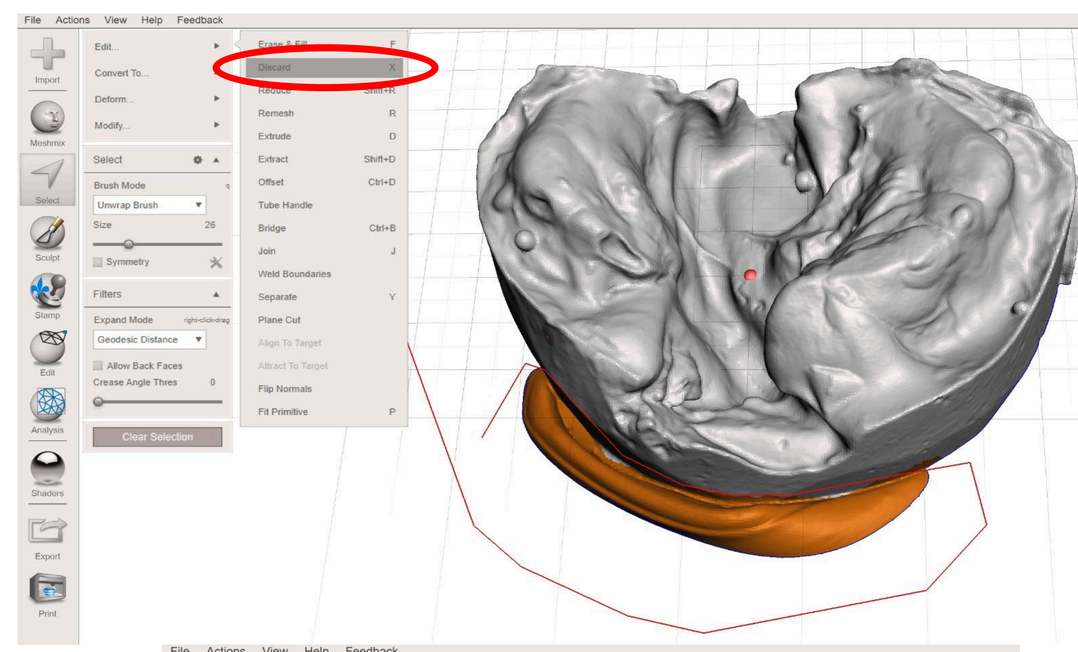


B. Model Trimming

Unnecessary mesh - such as over-scanned base regions or surrounding geometry - was removed using Meshmixer's Selection and Discard tools:

1. Activate the Select tool from the left-hand toolbar
2. Highlight unwanted regions using the brush interface (lasso select option also available)
3. Expand or contract the selection as needed using the selection menu
4. Discard the selection via:
    - Edit → Discard *(Keyboard shortcut: X)*

Note: Trim carefully around clinically relevant structures to preserve margins and undercuts critical for appliance fit.

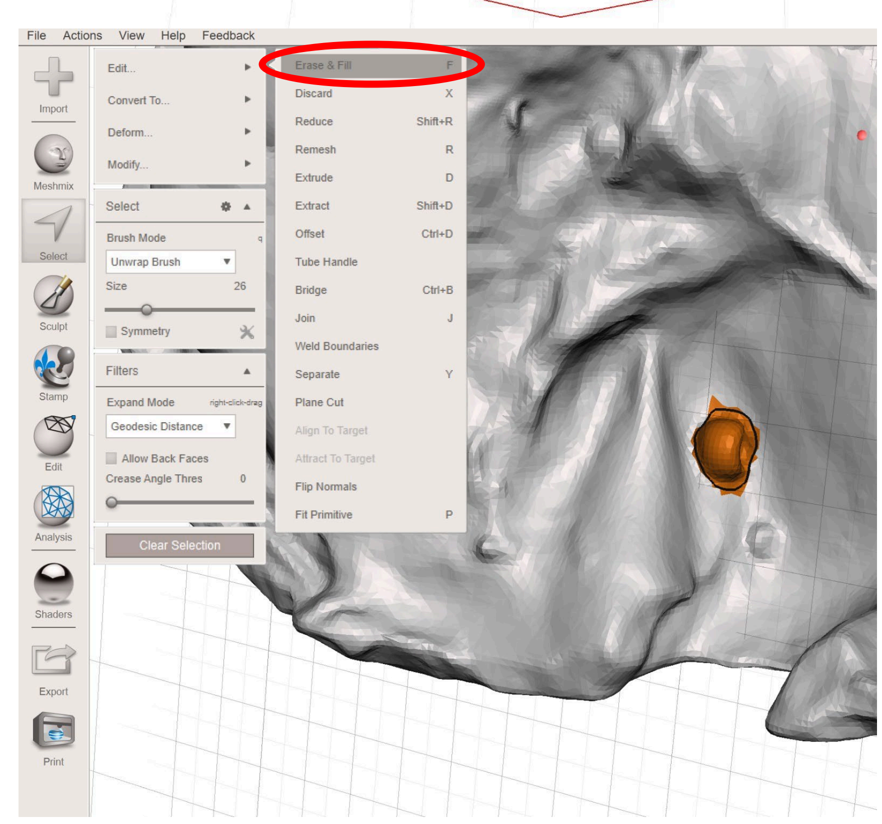


C. Cleaning the Mesh by Filling Voids & Positive Artifact Removal

Extraneous mesh projections (e.g., small bumps, scan spikes, or positive artifacts) were eliminated through targeted surface correction:

1. Use the Select tool to highlight the affected area.
2. Expand the selection boundary smoothly by pressing the "B" key multiple times until a clean perimeter is formed around the defect.
3. Apply the Erase & Fill tool:
    - Edit → Erase & Fill
    - This command deletes the selected region and replaces it with a planar surface conforming to the surrounding mesh.

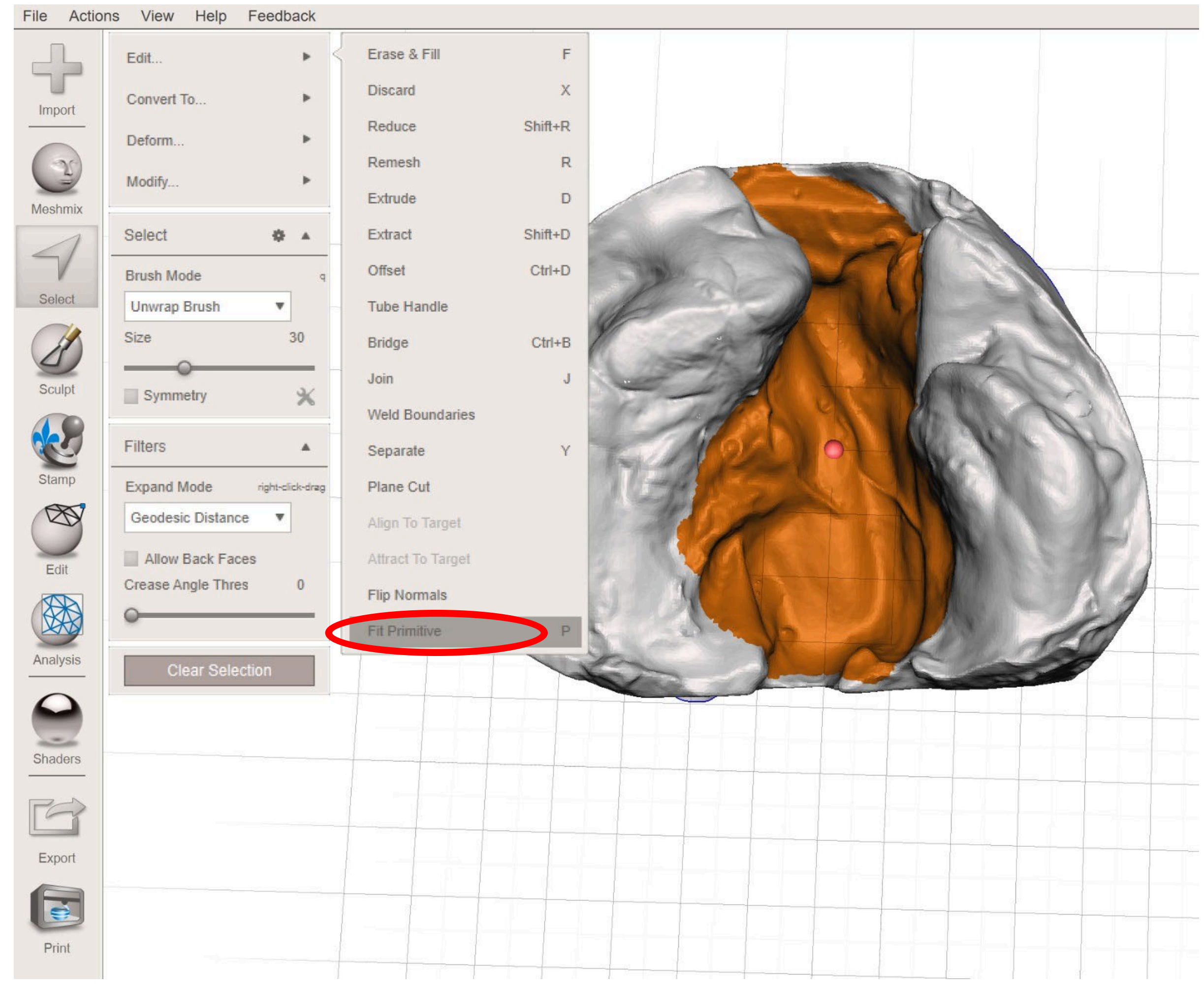
Tip: Although multiple methods exist for cleaning scan defects, the select → erase → fill approach is among the fastest and most efficient for localized artifact correction.



Supplemental Figure 2. (*Continued*)

Step 4: Cleft Palate Block-Out

Anatomical undercuts in the palatal region were digitally modified to facilitate proper appliance seating and removal. Without this block-out step, the resulting appliance may engage deep anatomical concavities - compromising both fit and function. Digital block-out allows the user to simulate traditional wax or putty block-out in a fully virtual environment, minimizing labor-intensive physical processing.

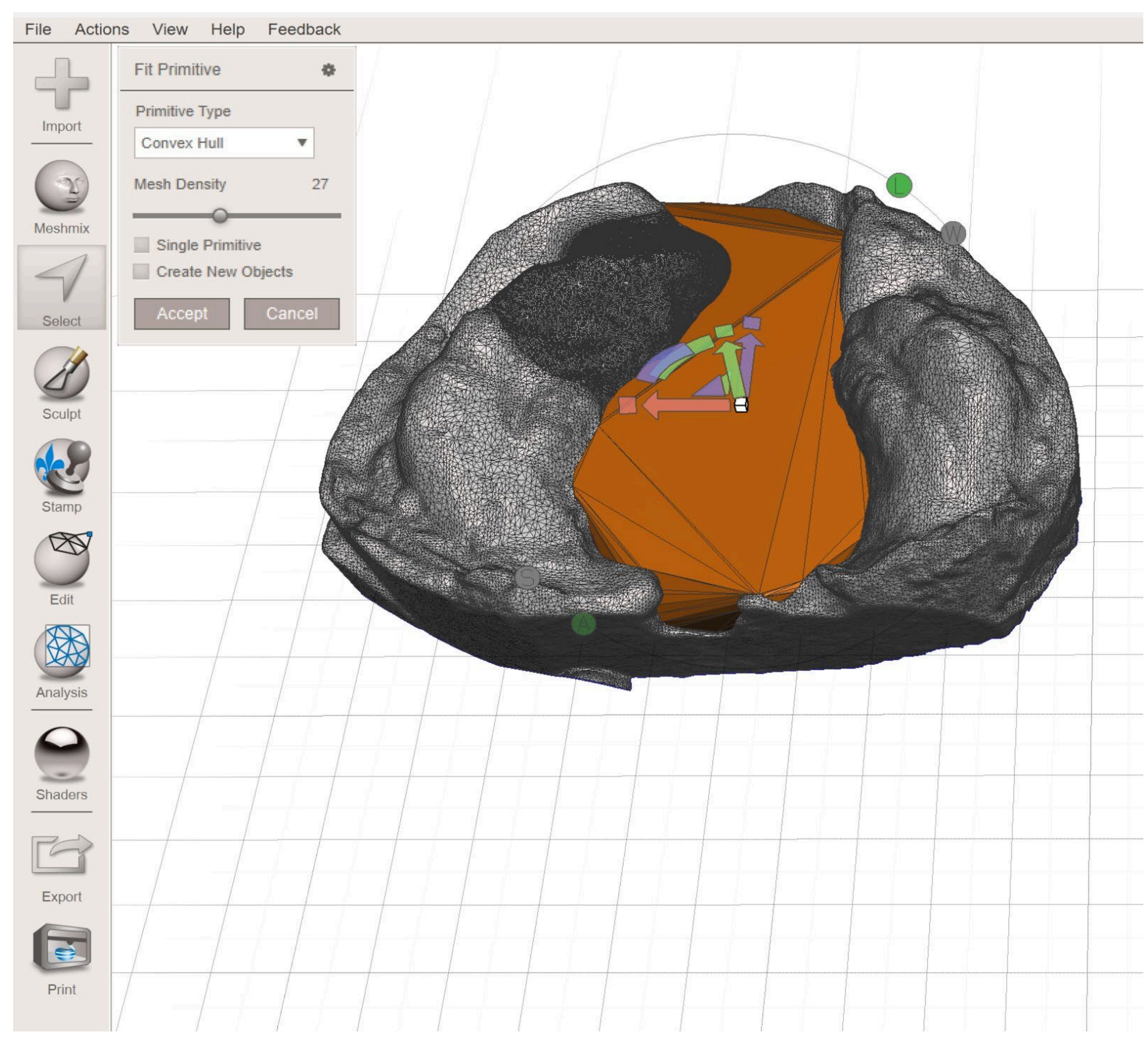


A. Cleft Palate Anatomy Identification

1. With the model fully oriented (see Step 2), the cleft region of the palate was evaluated for undercuts that would interfere with a passive path of insertion.
2. Areas of concern - typically located along the cleft margins, nasal floor, and medial aspects of the alveolar segments - were inspected from multiple angles using Meshmixer's rotation tools.
3. Once identified, the undercut region was selected using the Select tool:
   - Activate the Select tool from the left-hand toolbar
   - Use the adjustable brush to highlight the cleft area that requires modification
   - Selection may be refined using expansion (press "B") or contraction tools as needed

Clinical Note: The goal is to fill the cleft anatomy entirely and to eliminate the undercuts that would prevent the appliance from seating passively and being easily removed. Appliance retention should come from peripheral fit, not deep anatomical engagement.

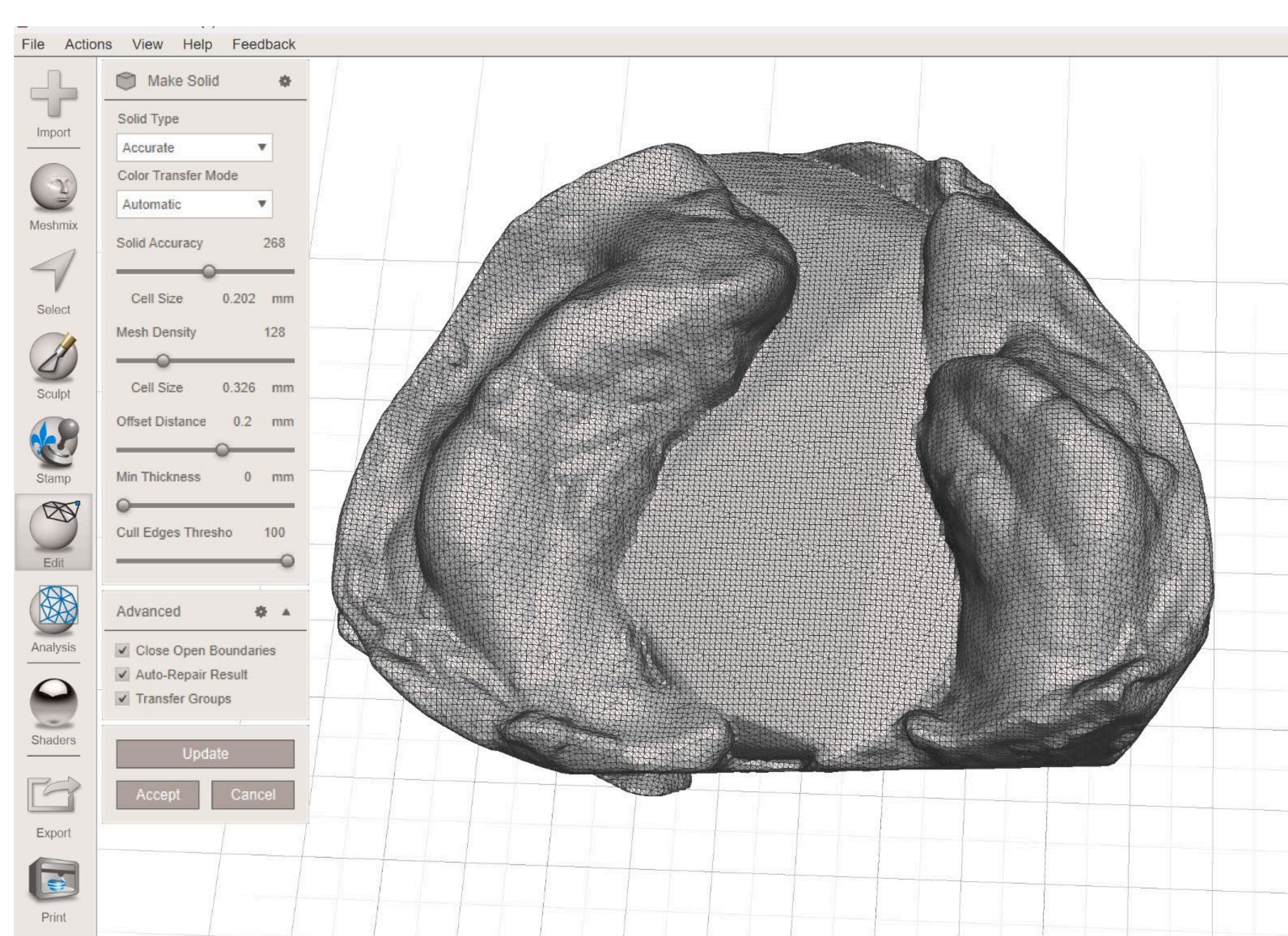
B. Block-Out Geometry Creation



1. With the undercut region selected, a convex hull primitive was generated to digitally simulate block-out material:
   - Navigate to: Edit → Fit Primitive
   - In the dropdown box, choose Convex Hull as the primitive type
   - Enable Single Primitive
2. Once generated, the convex hull was repositioned to simulate clinical block-out:
   - Use on-screen directional arrows (translation tools) to adjust the hull into the cleft defect
   - Adjust as needed in three dimensions to achieve the desired inferior block-out level
   - Ensure the geometry covers the targeted cleft palate area without encroaching on functional soft tissue space (avoiding the greater and lesser alveolar segments)
3. The resulting block-out hull creates a smooth, convex fill over the selected defect, facilitating the creation of a digitally passive appliance base

C. Mesh Solidification

This step harmonizes the previously modified cleft model (including the convex hull block-out geometry) into a new, smoothed, and watertight mesh. Simultaneously, it introduces a uniform **tissue relief offset**—a small separation (typically 100–200 µm) between the appliance and mucosa to prevent pressure, friction, or binding, and to account for material shrinkage during appliance fabrication.



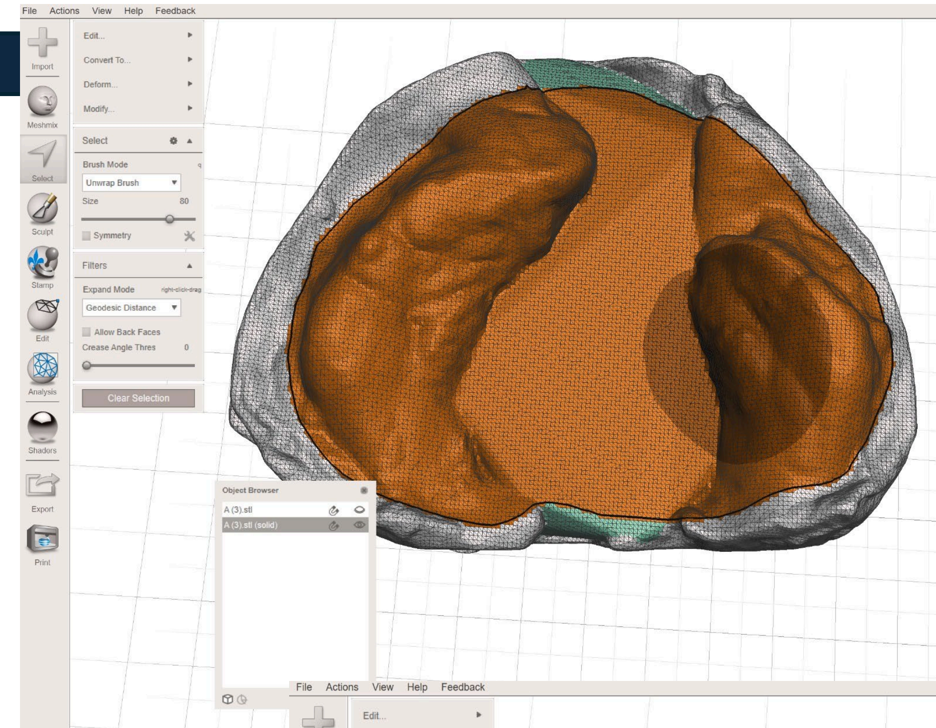
1. Select the entire modified model (including the block-out geometry).
2. Navigate to: Edit → Make Solid
3. In the Make Solid panel:
   - Set Solid Type = Accurate (this enables the Offset Distance input)
   - Set Offset Distance = 0.2 mm
     (This value provides both soft tissue relief and compensates for typical resin-based shrinkage in appliance manufacturing.)
   - Set Cell Size = 0.2 mm
     (This defines the resolution of the solid mesh and corresponds to high-quality fabrication standards used in orthodontic splints.)
   - Check "Transfer Groups" to preserve original segmentation if applicable
   - Click Update to preview changes
   - Click Accept to finalize the new solid mesh

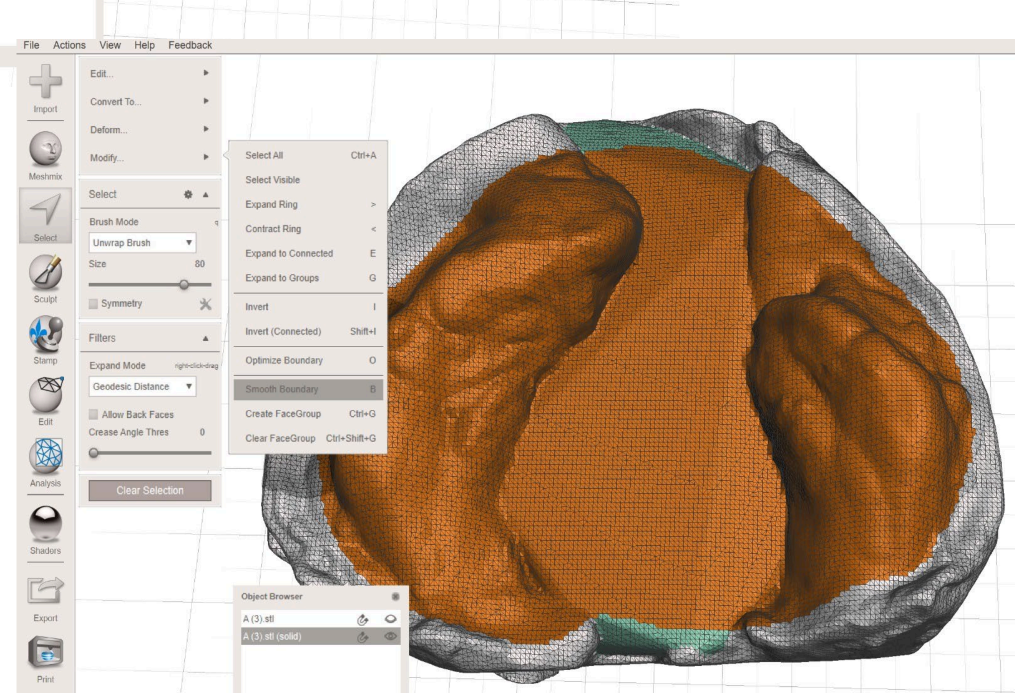
Note: A 0.2 mm offset (200 microns) represents a clinically validated relief for mucosal comfort and manufacturing tolerance. This process also ensures the resulting mesh has a uniform triangle substructure, free from gaps or inconsistencies caused by prior block-out steps.

Supplemental Figrue 2. (*Continued*)

Step 5: Digital Appliance Fabrication

Digital design of the NAM plate followed a standardized and repeatable protocol. This stage defines the appliance's extent, starting with the **basal seat**, which interfaces directly with the infant's maxillary anatomy. Accurate basal seat definition ensures passive fit, functional support, and proper adaptation of the molding elements.

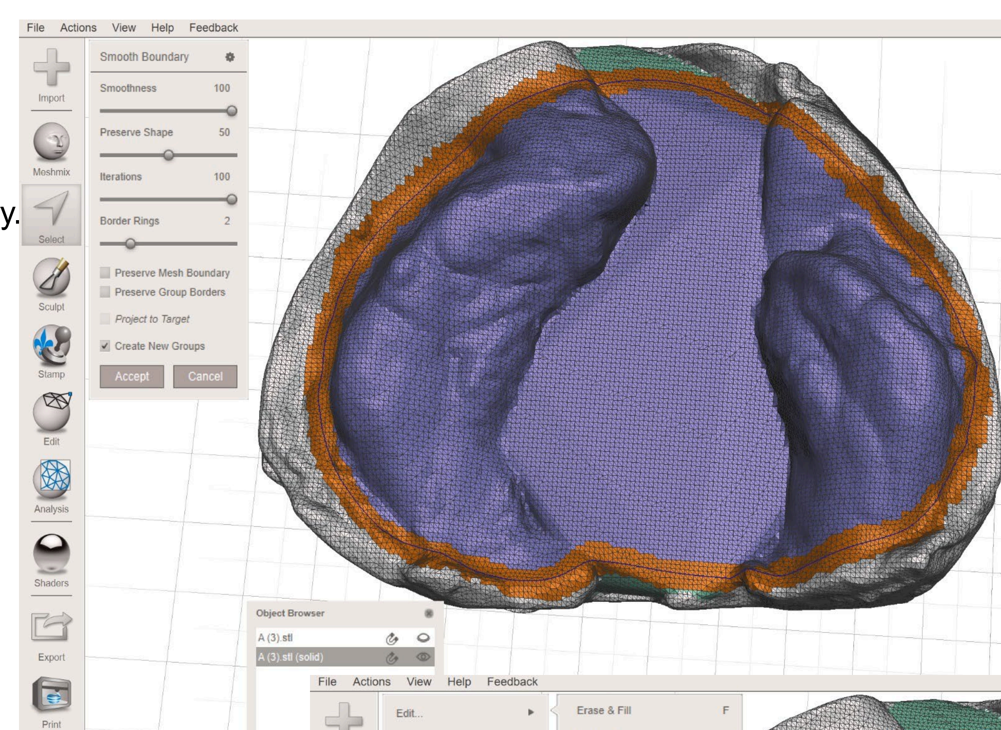




A. Basal Seat Definition

1. Within the solidified model layer (from Step 4C), the Select tool was used to define the appliance's basal seat:
   - Activate the Select tool from the left-hand toolbar
   - Use the Lasso mode (shortcut key: L) or standard brush selection to delineate the desired intaglio (tissue-contacting) surface of the NAM plate
2. The basal seat selection included:
   - The greater segment of the alveolar ridge
   - The lesser segment
   - The cleft-palate block-out region previously created
3. Smooth transition zones were maintained along the periphery to preserve anatomical conformity and avoid pressure points.
4. After the desired area was fully selected:
   - Create a new Face Group from the selection
     → Right-click the selection → Assign to Face Group

Note: Creating a distinct face group enables targeted editing in subsequent steps, including extrusion, sculpting, and appliance base isolation. The face group defines the foundational geometry for the NAM plate and should conform to clinical design parameters for extension, retention, and coverage.

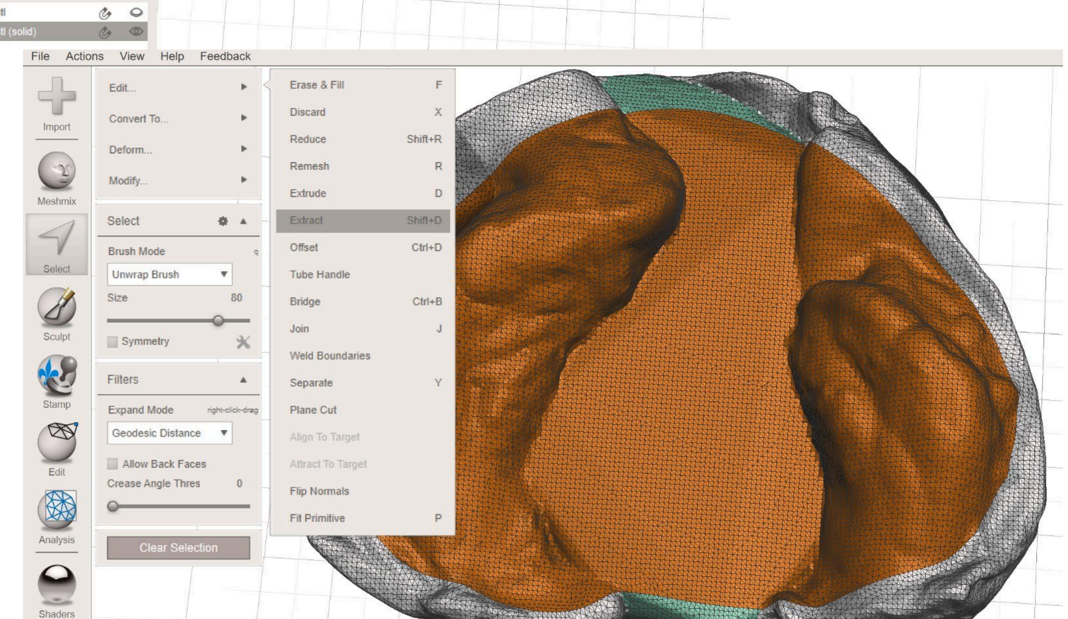


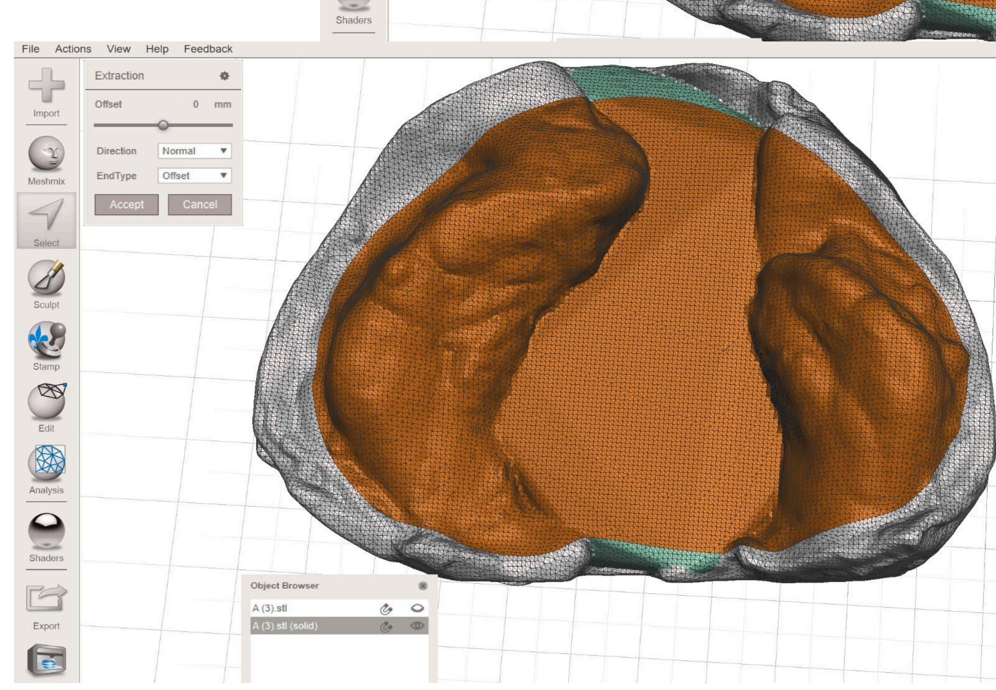
B. Boundary Smoothing of the Basal Seat Area

After the basal seat area was selected and assigned to a face group, the perimeter of the selected region was smoothed to create a continuous, non-abrupt transition between the appliance and the underlying anatomy. This step is essential to avoid sharp borders that could lead to discomfort or pressure points on the mucosa.

1. With the basal seat face group selected, click Modify → Smooth Boundary.
2. Adjust the Boundary Smoothness setting to create a gentle, anatomical taper between the selected area and surrounding mesh.
   - Recommended setting: Smoothness = 10–20 iterations (can be adjusted based on desired blending).
3. Visually inspect the transition zone to ensure an even, natural-looking contour along the basal seat edge.

Note: Smoothing the boundary before extrusion ensures that the future NAM plate edge conforms passively to the palatal surface and avoids sharp geometric transitions that could affect patient comfort or printability.





C. Duplicate the Basal Seat

Once the basal seat region was defined and smoothed, the selected area was extracted as a new surface to begin forming the NAM appliance base.

1. With the basal seat face group selected:
   - Activate the Select tool
   - Right-click the face group (or use Face Groups → Select Group) to reselect the defined region
2. Duplicate the selected surface using the **Extract** function:
   - Navigate to: Edit (under the Selection Tool menu) → Extract
   - In the Extract dialog, leave the default settings or set Offset to 0 mm to create an exact duplicate of the selected area
3. Click Accept to generate a new, independent mesh object of the basal seat
   - This new object will appear in the Object Browser as a separate item, typically named "Extracted Part"

Note: The extracted basal seat surface will serve as the foundation for thickening and further shaping of the NAM plate. At this stage, it remains a thin shell identical to the selected intaglio surface.

Supplemental Figure 2. (*Continued*)

C. Duplicate the Basal Seat (Continued)

4. Separate the copied surface by selecting it then clicking “Separate” from Main Menu
- “Select Tool” → “Edit” → “Separate”.

D. Plate Thickness Application

To convert the extracted basal seat shell into a printable appliance, a uniform thickness was applied by offsetting the entire surface outward.

1. Ensure the extracted basal seat mesh (created in Step C) is selected in the Object Browser.
   - Select the entire surface:
   - Press Ctrl + A
   - Or go to Select → Select All
2. Apply a uniform thickness:
   - Navigate to: Edit → Offset
3. In the Offset dialog box, set the following parameters:
   - Offset Distance = 3 mm
   - Offset Type = Normal
   - Soft Transition = 0 mm
   - Direction should remain Outward (default)
4. Click Accept to generate a thickened, closed-surface NAM plate.

Note: A 3 mm uniform plate thickness provides structural durability appropriate for neonatal appliance use while remaining within typical biocompatible resin tolerances. A Soft Transition of 0 mm maintains geometric fidelity to the original intaglio surface, ensuring accurate adaptation without rounding of margins.

E. Smoothing the Outer Surface and Margin

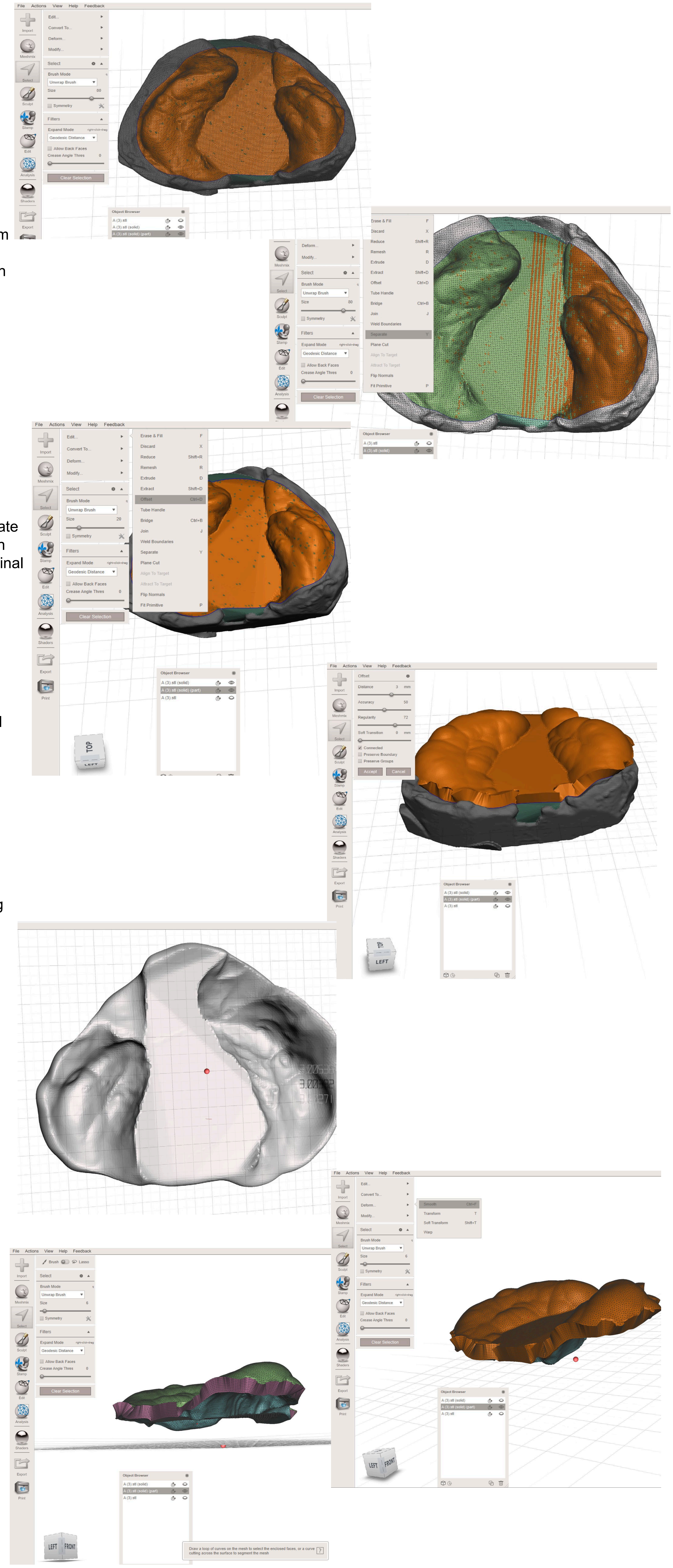
After generating the thickened appliance geometry, the outer (external) surface and margin of the NAM plate were selectively smoothed to improve comfort, remove sharp edges, and enhance printability. This finishing step ensures a patient-safe interface while preserving the appliance’s anatomical fidelity.

Important: The intaglio (tissue-contacting) surface must remain untouched during this step. Smoothing the intaglio can compromise appliance fit and negate the digital tissue relief created in Step 4C.

Procedure:

1. Select the outer surface and margin only:
   - Activate the Select tool
   - Carefully highlight the external/top surface and plate edges using the brush or lasso mode
   - Avoid including any of the internal (intaglio) surface in the selection
2. Apply surface smoothing:
   - With the selection active, press Ctrl + F *(keyboard shortcut for “Smooth”)*
     - Alternatively, right-click the selection and choose Smooth from the context menu
   - Adjust smoothing parameters as needed:
     - Smoothing Strength = moderate (e.g., 10–20)
     - Use multiple passes if necessary to achieve a clean, rounded contour
3. Visually inspect the appliance:
   - Ensure the outer surface is uniformly smooth
   - Margins should appear softened and free of sharp geometry
   - Confirm that no changes have been made to the intaglio surface

Tip: If localized refinement is needed (e.g., around the anterior flange or lateral extensions), use the Sculpt Tool → Smooth Brush for manual adjustments.



Supplemental Figure 2. (*Continued*)

Step 6: Appliance Accessories

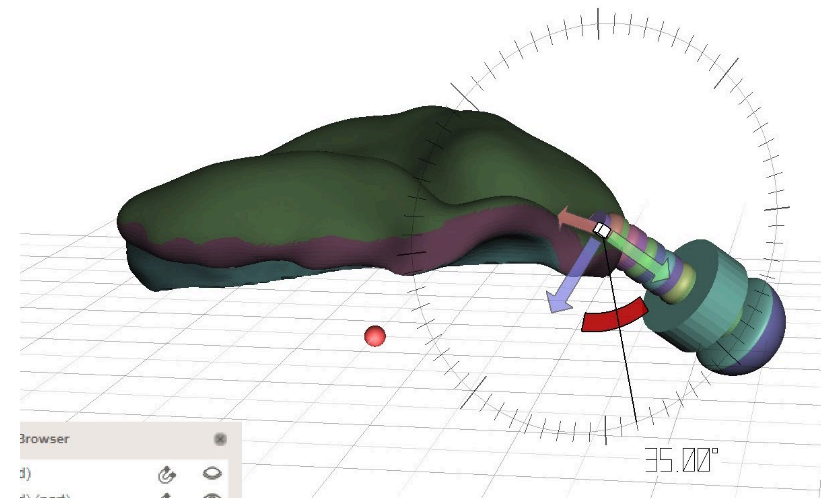
Additional appliance features such as drainage holes or anatomical vents can be digitally incorporated to enhance hygiene, comfort, and clinical usability. These modifications are performed after the core NAM plate has been finalized and smoothed.

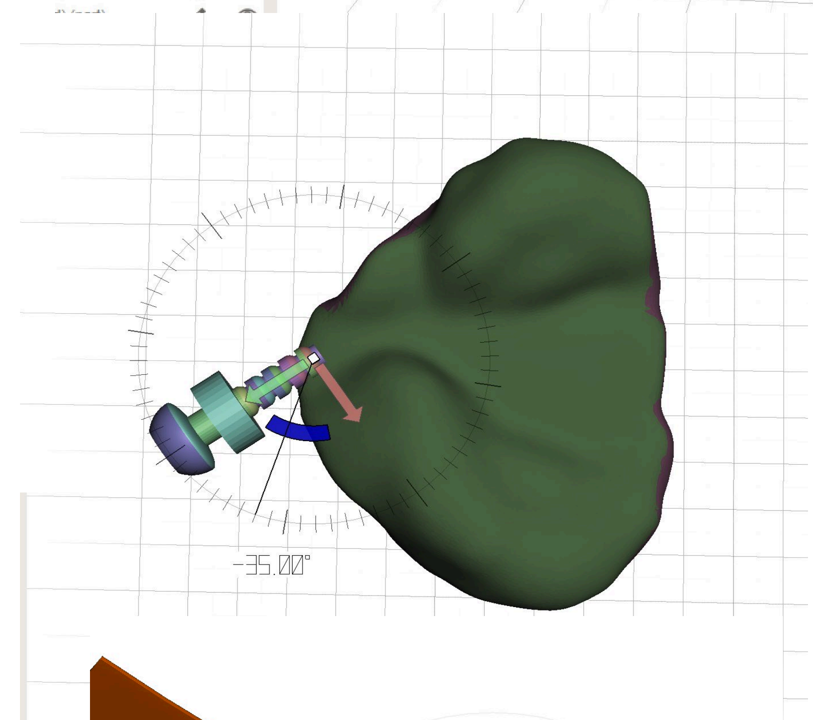
A. Adding Retention Button

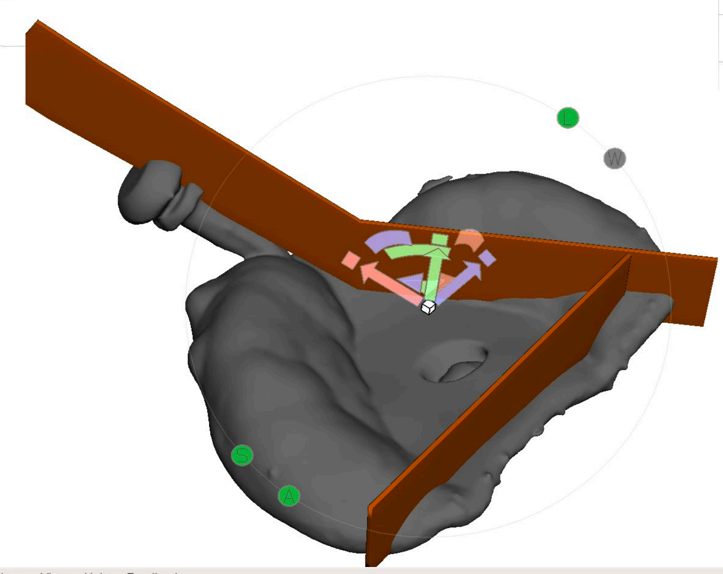
A digital retention button was added to the NAM plate to allow elastic attachment and gentle orthopedic guidance. The button was positioned and angled according to anatomical landmarks and soft tissue considerations.

1. Identify the button site:
   - Locate the button over the alveolar ridge of the greater segment
   - Button position should allow unobstructed elastic connection from the prolabium or lip taping system
2. Determine retention button specifications:
   1. Length = 12–15 mm, depending on soft tissue thickness
   2. Vertical angulation = ~35° from the maxillary alveolar plane
   3. Horizontal (mediolateral) angulation = aligned using a virtual reference line drawn across the tuberosity of the lesser segment
3. Create the button using a primitive:
   - Click the Meshmixer icon on the main toolbar
   - Go to Parts Library → Primitives
   - Select and drag a Cylinder onto the desired location
4. Adjust button dimensions and orientation:
   - Modify cylinder length to 12–15 mm
   - Tilt the cylinder ~35° vertically relative to the alveolar ridge
   - Rotate mediolaterally to align with the anatomical reference line
5. Convert to solid and attach:
   - Ensure the cylinder is a separate object in the Object Browser
   - Use Boolean Union to permanently attach the button to the NAM plate:
     → Edit → Boolean Union
     → Select the NAM plate and button cylinder
     → Click Accept

Note: The digital button shape and taper can be refined using the Sculpt Toolset if needed for anatomical clearance or elastic retention compatibility. We designed a button positioning jig to help standardize the design process.







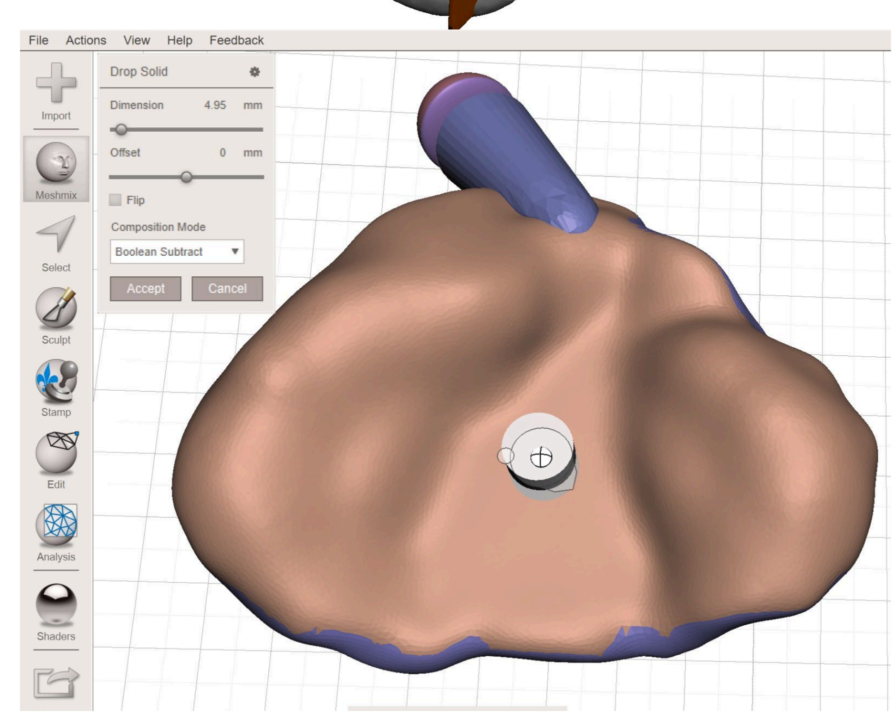
B. Ventilation Hole Creation

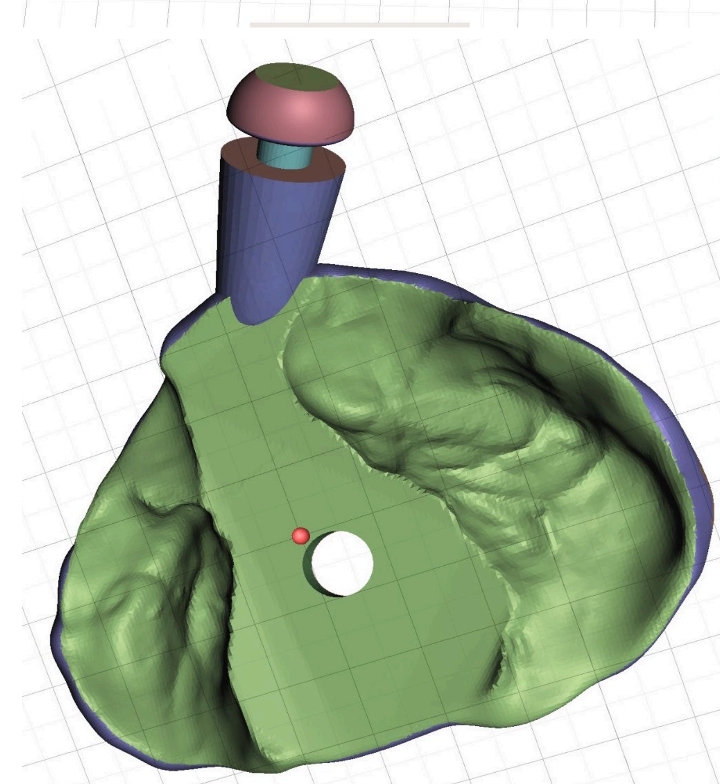
To prevent moisture accumulation beneath the appliance and reduce the risk of irritation or fungal growth, a drainage hole was added. The hole was designed to maintain structural integrity while allowing for airflow and drainage.

1. Add a cylindrical primitive:
   1. Select the Meshmixer icon (main menu)
   2. Open the Parts Library → choose Primitives
   3. Drag and drop a Cylinder onto the desired location on the appliance
2. Adjust the cylinder dimensions:
   - Set Diameter = 5 mm
   - Extend the Height to fully penetrate the thickness of the NAM plate
   - Rotate the cylinder to introduce a 5° angulation from vertical, improving drainage without compromising plate integrity
3. Convert the cylinder to solid geometry:
   - Ensure the cylinder is selected
   - In the Object Browser, confirm it is listed as a separate solid object
4. Prepare for subtraction (to create the hole):
   1. Use Boolean Difference:
      Edit → Boolean Difference
      1. Select the NAM plate as the target
      2. Select the cylinder as the subtractive object
      3. Apply the operation to cut the hole

Tip: You can adjust the size, shape, and number of holes depending on drainage requirements or provider preference. The angled entry helps reduce direct fluid pooling while maintaining strength across the plate.

* Button STL file available for download





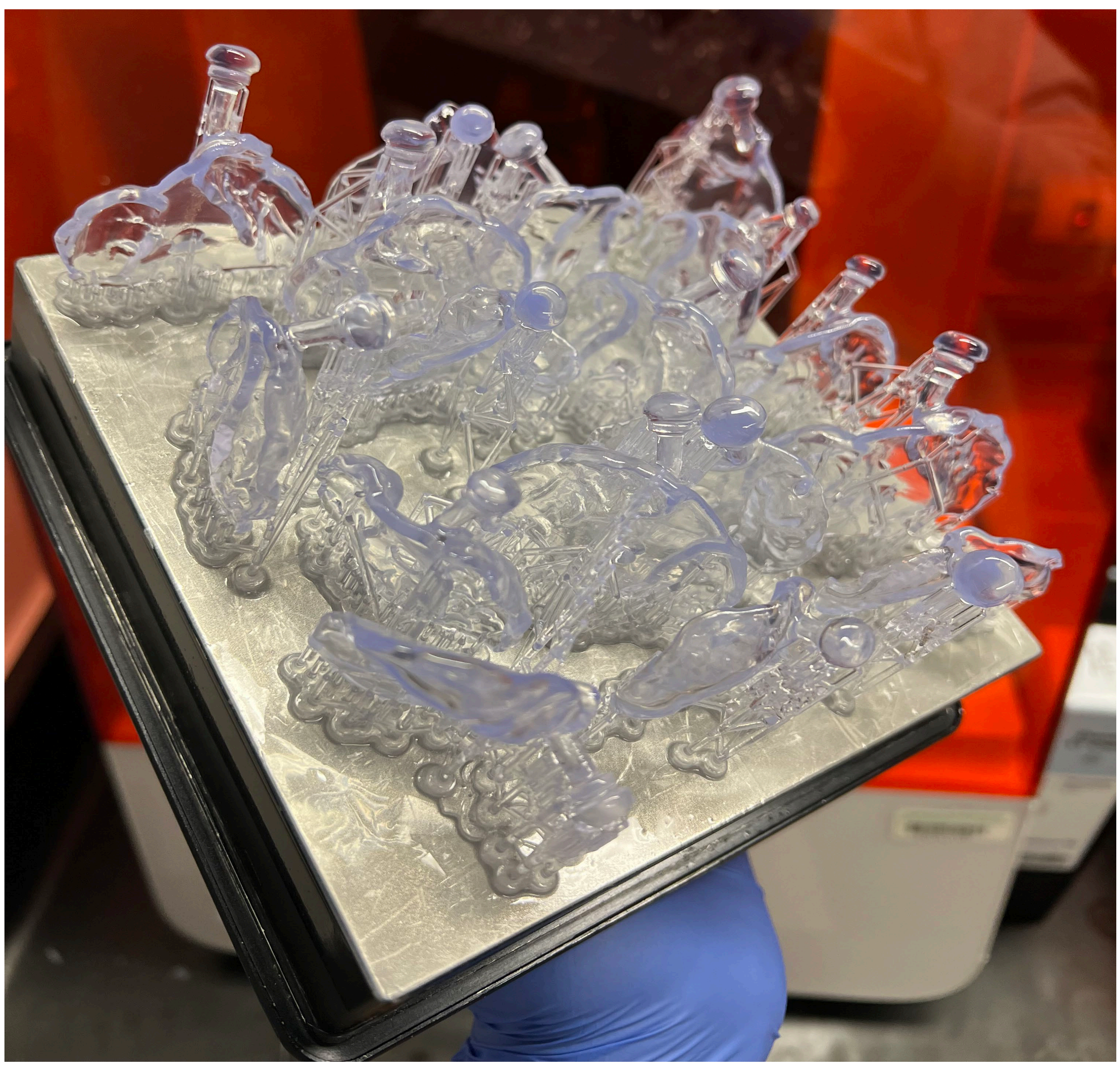
Supplemental Figure 2. (*Continued*)

Step 7: File Preparation and Manufacturing

Once the NAM appliance design—including base, block-outs, and accessory features—was finalized, the file underwent final inspection and preparation for 3D printing.

1. Final Inspection
   - The appliance mesh was reviewed to confirm complete integration of all components (e.g., retention button, drainage hole), absence of non-manifold edges, and watertight geometry
   - The Analysis → Inspector tool was used to identify and resolve any remaining mesh defects
2. Exporting the File
   - The finalized appliance was exported in STL (Standard Tessellation Language) format
   - Export settings were set to High Resolution to preserve the fidelity of the smooth contours and precise fit
3. Import into Print Preparation Software
   - The STL file was imported into PreForm software (Formlabs Inc.) for print preparation
   - The model was oriented to optimize print success, surface quality, and support placement
     - Common orientation: plate angled at ~45° to build platform
   - Supports were auto-generated and manually refined to avoid contact with the intaglio surface or retention button
4. Print Settings & Manufacturing
   - The file was prepared for stereolithography (SLA) printing using biocompatible resin
   - Printer: Formlabs Form 3B+
   - Layer height: typically 50 microns (adjustable based on appliance requirements)

Note: Orientation and support placement are critical to preserving intaglio fidelity and reducing post-processing time. Avoid placing supports on the internal surface or edges that contact soft tissue.



Supplemental Figure 3

Accuracy Assessment

Surface Deviation Analysis Protocol

Appliance accuracy was assessed through comprehensive surface deviation analysis using CloudCompare software (version 2.12.4, open-source 3D point cloud and mesh processing software). Both conventional and digital NAM appliances were digitized using the desktop 3Shape scanner (E4) with identical scanning parameters (50-micrometer resolution) to ensure measurement consistency.

CloudCompare Surface Comparison Methodology

The surface comparison analysis followed a standardized protocol:

1. **Data Import and Registration**: Three STL files were imported for each sample: (1) the original gypsum cast scan (reference), (2) the conventional NAM appliance scan (comparison 1), and (3) the digital NAM appliance scan (comparison 2). All meshes underwent initial quality inspection to verify complete surface capture and adequate point density.
2. **Mesh Alignment and Registration**: Precise spatial alignment between reference and comparison meshes was achieved using CloudCompare's Iterative Closest Point (ICP) algorithm. Initial coarse alignment was performed manually using anatomical landmarks (incisive papilla, palatal rugae, and alveolar ridge contours), followed by fine registration using ICP with convergence criteria set to 0.001mm root mean square (RMS) error.
3. **Surface-to-Surface Distance Calculation**: CloudCompare computed perpendicular distances from each point on the appliance surface mesh to the nearest corresponding point on the reference cast surface. The software calculated these distances using a k-nearest neighbor search algorithm with k=6 to ensure robust surface correspondence even in areas of complex curvature.
4. **Statistical Analysis Parameters**: The following statistical measures were extracted for each comparison:
   - Mean absolute deviation (mm)
   - Standard deviation (mm)
   - Root mean square deviation (mm)
   - Maximum positive deviation (mm)
   - Maximum negative deviation (mm)
   - 95th percentile deviation values

Heat Map Visualization and Interpretation

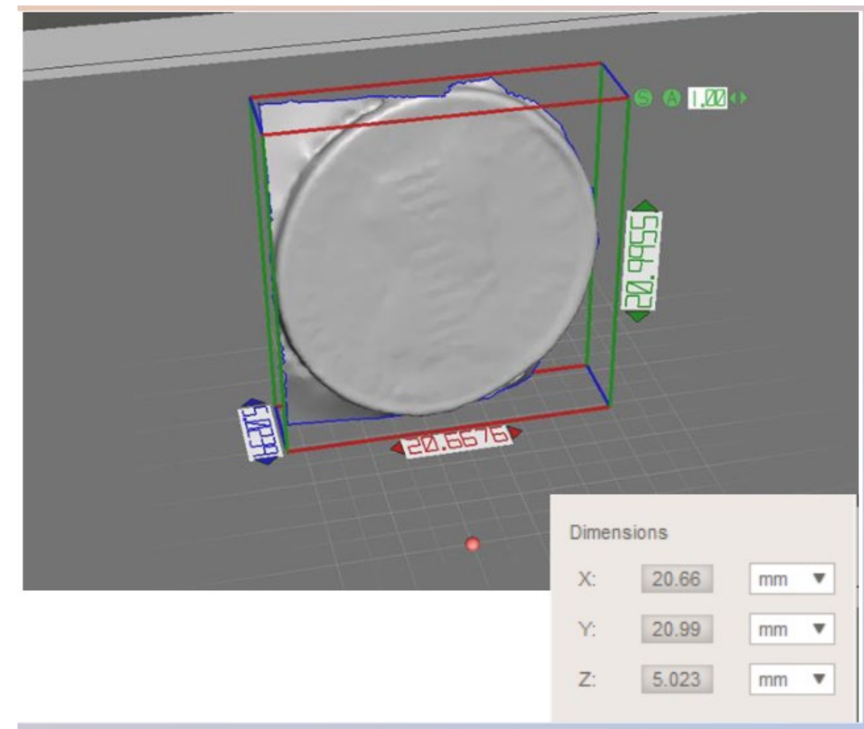
CloudCompare generated color-coded heat maps displaying surface deviation patterns across the entire appliance-cast interface:

1. **Color Scale Calibration**: A standardized color scale was applied across all comparisons ranging from -2.0mm to +2.0mm deviation. The scale utilized a spectrum from blue (negative deviations) through green (minimal deviation) to red (positive deviations).
2. **Deviation Interpretation**:
   - **Blue regions** (negative values): Indicate appliance under-contouring where the NAM surface lies inside/below the reference cast surface, potentially causing poor tissue contact or retention issues.
   - **Green regions** (near-zero values): Represent optimal appliance fit with minimal surface deviation (<0.2mm), indicating accurate tissue adaptation.
   - **Yellow to red regions** (positive values): Show appliance over-contouring where the NAM surface extends beyond the reference cast surface, potentially causing pressure points or tissue trauma.
3. **Regional Analysis**: Heat maps were systematically evaluated across anatomically distinct regions:
   - **Alveolar ridge areas**: Critical for appliance retention and stability
   - **Palatal vault**: Important for proper tissue support and feeding function
   - **Cleft margins**: Essential for gap reduction and tissue molding efficacy
   - **Transition zones**: Areas between segments requiring smooth contour integration
4. **Quantitative Measurements**: For each heat map, surface area percentages were calculated for different deviation ranges:
   - Excellent fit: ±0.2mm deviation (target >70% surface area)
   - Acceptable fit: ±0.5mm deviation (target >90% surface area)
   - Poor fit: >±1.0mm deviation (target <5% surface area)

Supplemental Figure 4

Calibration Exercise for Cloud Compare

A penny of known dimensions (X-20.66mm,Y-20.99mm,Z-5.023mm) was digitized using a high-resolution desktop 3Shape, E4 scanner. The resulting scan was exported in STL format and saved as *penny.stl*. This file was imported into **Cloud Compare** (.stl) for subsequent analysis.



For alignment, the *penny.stl* model was overlapped on itself using the Iterative Closest Point (ICP) algorithm. The registration was performed with 49975 points, applying the following transformation matrix: {0,1,0,0} {0,0,1,0} {0,0,0,1} During cloud registration, one STL was designated as the reference mesh and the other as the aligned mesh. To distinguish them visually, the reference mesh was color-coded yellow, while the aligned mesh was color-coded red. The ICP process was executed over 20 iterations, resulting in a final overlap of 100%.A heat map of the overlapped models was generated, which appeared completely blue, indicating a perfect correspondence between the two datasets. The analysis yielded a mean distance of 0.0 mm and a standard deviation of 0.0 mm, confirming identical alignment. Cloud Compare computes the distance between corresponding points of the reference STL and the aligned STL to generate its statistical outputs. As the input STL model was defined in millimeters, all measurements in Cloud Compare were accordingly referenced to millimeters.