Chapter

Patient-Specific 3D-Printed Models for Simulation-Supported Surgical Planning in Complex Pediatric Nasal Surgery – A Reproducible Workflow

Mathilde Gregoire, Cédric Detry, Olivier Bouchain, Nicolas Peigneux, Alexandre Ghuysen, Unal Duran and Florence Rogister

Abstract

Simulation-based strategies are increasingly recognized as important tools for surgical education, interdisciplinary communication, and patient safety. In pediatric surgery, realistic simulation remains challenging because indications may be rare, anatomical dimensions are small, and ethical constraints limit opportunities for rehearsal on patients. This chapter presents a reproducible workflow for simulation-supported preoperative planning using patient-specific three-dimensional (3D)-printed models in complex pediatric nasal surgery. The workflow is illustrated through the case of a 10-month-old infant with nasal glial heterotopia involving the nasal pyramid and nasal cavities. Computed tomography and magnetic resonance imaging data were processed to generate a patient-specific anatomical model, which was printed at 1:1 scale using fused deposition modeling and multicolor polylactic acid (PLA). The model was used for operative planning, instrument compatibility assessment, structured team briefing, parental counseling, pathology orientation, and undergraduate and postgraduate education. By linking predefined clinical and educational objectives to a practical imaging-to-printing workflow, this chapter shows how patient-specific 3D printing can bridge imaging, simulation, surgical preparation, communication, and education within a university hospital simulation center. Limitations include the single-case experience, resource requirements, dependence on segmentation expertise, limited material realism, and absence of prospective outcome measurement. Future perspectives include educational evaluation, extension to other pediatric ENT indications, integration with virtual or augmented reality, and objective assessment within a structured simulation curriculum.

Keywords: patient-specific three-dimensional printing, surgical simulation, pediatric nasal surgery, rhinologic surgery, preoperative planning, medical education, simulation center, glial heterotopia

1. Introduction

Simulation has become an essential component of modern healthcare training and patient safety strategies. In surgery, its purpose is not limited to reproducing a technical gesture; it creates a structured environment in which clinicians can acquire, rehearse, and refine technical and nontechnical competencies before encountering high-risk situations with patients [1, 2].

Patient-specific three-dimensional (3D) modeling and printing extend this concept by transforming clinical imaging into tangible anatomical representations. Imaging-derived models can complement conventional preoperative planning by helping clinicians move from two-dimensional (2D) image interpretation to a spatial, tactile understanding of the individual patient's anatomy [3, 4]. Recent pediatric surgery reviews emphasize the relevance of this approach in children because of small anatomical dimensions, congenital variability, and the need to individualize surgical planning while minimizing avoidable risk [5, 6].

Otorhinolaryngology (ENT) is particularly well suited to simulation-based education. ENT surgery requires precise anatomical understanding, 3D spatial orientation, manual dexterity, and the ability to operate within narrow and functionally critical spaces. In rhinology, surgeons must mentally reconstruct complex anatomy from endoscopic views and multiplanar imaging while considering the proximity of the orbit, skull base, neurovascular structures, and the developing craniofacial skeleton.

Traditional surgical education still relies heavily on apprenticeship. This model remains central to surgical identity, but it is increasingly constrained by patient safety requirements, limited operative time, variable exposure to rare cases, and the need for reproducible competency-based training. A national Belgian survey of ENT trainees highlighted persistent gaps in practical surgical training and identified simulation as a potential tool to structure technical learning [7]. In addition, spatial orientation has been shown to influence performance in endoscopic sinus tasks, supporting the educational relevance of tools that make complex anatomy more explicit and manipulable [8].

In rhinology and endoscopic skull base surgery, 3D printing has been described for preoperative surgical planning, patient education and trainee education [9]. Dedicated patient-specific or standardized 3D-printed sinus simulators have also been developed for endoscopic sinus surgery training, with reported value for anatomical fidelity, haptic feedback, and repetitive skills acquisition [10, 11]. However, published workflows remain less frequent for rare pediatric nasal indications, particularly when the model is used simultaneously for operative preparation, instrument compatibility testing, team briefing, parental counseling, pathology orientation, and integration into a simulation center curriculum.

The primary educational audience for this workflow is ENT trainees, including residents and fellows in rhinology or pediatric ENT, together with simulation faculty who design structured learning activities around real clinical cases. For these

users, the model is intended not only as an anatomical display but also as a platform for objective assessment, including spatial orientation tasks, model-based surgical planning checklists, instrument-selection exercises, and observed team-briefing behaviors.

Complex pediatric nasal surgery combines several challenges: rare indications, limited working space, restricted opportunities for rehearsal, and high expectations regarding safety and precision. Patient-specific 3D printing may therefore be viewed as a modern form of augmented apprenticeship: a way to analyze, discuss, rehearse, and teach a real case outside the operating room. Against this background, this chapter presents a reproducible simulation-supported workflow using patient-specific 3D modeling and printing for preoperative planning in complex pediatric nasal surgery. A rare case of nasal glial heterotopia in a 10-month-old infant is used as the clinical anchor, while the workflow elements are deliberately described in a way that can be adapted by other centers with different levels of technical and simulation resources.

2. Clinical and educational objectives of the workflow

2.1 Clinical objectives

Before implementing patient-specific 3D printing in clinical practice, the objectives of the model must be explicitly defined. Without clear objectives, 3D printing may remain an attractive technological add-on rather than a meaningful clinical and educational tool.

In the present workflow, the clinical objectives were to improve preoperative anatomical understanding, support selection and confirmation of the surgical approach, anticipate technical constraints related to infant nasal dimensions, verify surgical instrument compatibility, and reduce uncertainty before entering the operating room. In infants, the discrepancy between enlarged radiological displays and real surgical dimensions can be substantial. A 1:1 model helps the surgeon appreciate actual working space and identify potential access limitations.

2.2 Interdisciplinary and communication objectives

The interdisciplinary objective was to promote a shared mental model among surgeons, anesthesiologists, nurses, radiologists, simulation specialists, and pathologists. Complex pediatric surgery requires coordinated anticipation of positioning, airway management, surgical access, bleeding risk, specimen handling, and postoperative care. A physical model provides a common visual and tactile reference around which team members can discuss the procedure.

The communication objectives included parental counseling. Explaining a rare congenital nasal lesion and its surgical management to parents can be difficult when relying only on CT or MRI slices. A 3D-printed model can translate complex anatomy into a more intuitive representation, thereby supporting the explanation of the lesion, the operative approach, and the constraints inherent to pediatric nasal surgery.

2.3 Educational objectives

The educational objectives were to expose medical students, residents, and fellows to rare pediatric nasal anatomy in a safe and reproducible manner. Rare congenital lesions may be encountered only once or a few times during an entire training pathway. Patient-specific models, therefore, provide ethically acceptable teaching resources that can be reused for anatomical orientation, procedural reasoning, and discussion of surgical strategy.

The model also supports nontechnical learning. During a structured session, trainees can be asked to present the case, identify key anatomical landmarks, propose an operative strategy, anticipate complications, and communicate the plan to the team. In this way, the model can be integrated into a broader simulation curriculum rather than used only as an anatomical display. These predefined clinical, communication, and educational objectives are revisited in the Discussion as the basis for interpreting the value, limitations, and future evaluation of the workflow.

3. Clinical case used as a workflow anchor

3.1 Clinical presentation and diagnosis

A 10-month-old infant presented with a congenital left-sided nasal mass responsible for persistent unilateral nasal obstruction and mild feeding difficulties. Clinical assessment suggested a complex lesion involving the nasal pyramid and nasal cavities. Because congenital midline or paramedian nasal masses may include lesions with intracranial extension or vascular components, multimodal imaging was required before definitive surgical management.

Preoperative imaging included high-resolution computed tomography (CT) of the facial skeleton and magnetic resonance imaging (MRI) (**Figure 1**). The CT provided detailed information regarding bony anatomy and surgical access. MRI provided superior soft-tissue characterization and was essential for excluding intracranial continuity. Imaging showed a well-defined lesion without intracranial extension or vascular features. Biopsy confirmed nasal glial heterotopia, a rare benign congenital lesion composed of mature ectopic glial tissue. Imaging is central to the assessment of congenital developmental nasal masses, and histological sampling should only be considered after secure exclusion of intracranial extension [12].

3.2 Surgical strategy, operative technique, and outcome

Complete surgical excision was planned using a combined endoscopic endonasal and external transcolumellar approach. Because of the patient's young age, restricted anatomical field, and rare pathology, the case was considered appropriate for simulation-supported preparation using patient-specific 3D printing. The model was created through collaboration between the Department of Otorhinolaryngology, the Department of Medical Imaging, and the institutional Medical Simulation Center. The clinical objective was not to replace conventional imaging or surgical expertise, but to complement them by creating a physical representation of the patient's anatomy before surgery.

Preoperative assessment identified two complementary components of the mass. The endonasal component was pedunculated laterally at the piriform aperture and

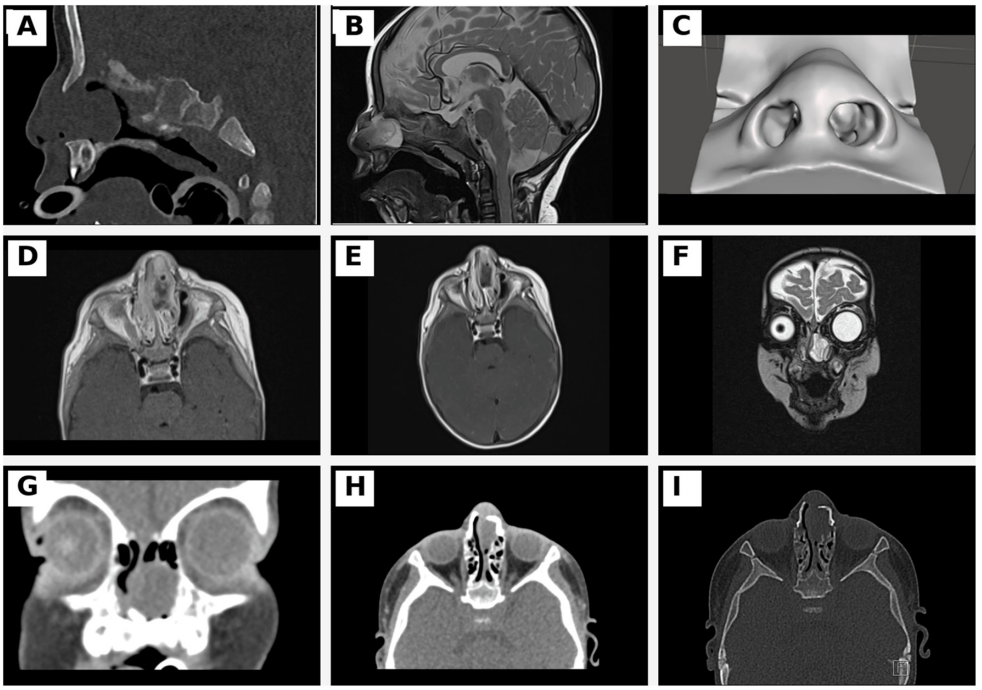


Figure 1.
Preoperative multimodal imaging and surface reconstruction: (a) Sagittal computed tomography (CT) image, bone window, illustrating the osseous anatomy and spatial relationship of the lesion within the nasal cavity. (b) Sagittal magnetic resonance imaging (MRI) demonstrating the endonasal and extranasal components of the lesion. (c) Three-dimensional surface rendering of the external nasal anatomy used during model generation. (d–e) Axial MRI views illustrating the lesion and its relationship to the nasal cavities and anterior skull base. (f) Coronal T2-weighted MRI showing the lesion and absence of intracranial continuity. (g–i) Coronal and axial CT views showing the relationship between the lesion, nasal cavities, ethmoid region, and developing facial skeleton. These complementary imaging modalities were used for segmentation, 3D reconstruction, and surgical planning.

extended medially through the nasal isthmus toward the superior septum. Anteriorly, it reached the posterior border of the alar cartilage; posteriorly, it extended to the head of the middle turbinate without invasion. A second smooth subcutaneous component was located over the nasal dorsum, overlying the nasal bones, and communicated with the endonasal lesion through a neck at the chondro-osseous junction between the upper lateral cartilage and the distal nasal bones.

The resection began endonasally. Using a Colorado needle monopolar electrode, the inferior, lateral, and anterior margins were outlined until the subperiosteal and subperichondrial planes were reached. Medially, an inferior margin was marked along the septal mucosa and connected to the anterior margin. The lesion was then dissected laterally and anteriorly in the subperiosteal and subperichondrial planes, allowing the mass to be mobilized posteriorly within the nasal cavity.

An external transcolumellar approach was then performed through an inverted-V columellar incision. Subcutaneous flap elevation exposed the alar cartilages and allowed dissection toward the nasal dorsum and the subcutaneous portion of the tumor. The dorsal component, which appeared firm, smooth, and whitish, was dissected progressively above the nasal bones in the subperiosteal and subcutaneous planes, with release of the superficial musculoaponeurotic soft-tissue envelope until

the communicating neck with the endonasal component was reached. A small accidental left paramedian skin breach occurred at the radix, where the tumor was adherent to the skin plane; it was closed with three 5-0 Ethilon sutures.

Endoscopic reassessment was then performed to define the posterior margins at the level of the ethmoidal bulla and the head of the middle turbinate, and at the corresponding septal level. These posterior margins were completed using the Colorado needle until the bony vault was reached. This allowed completion of the posterior section of the mass, delivery of the dorsal component into the nasal cavity, and *en bloc* removal of the specimen. After resection, a support defect of approximately 5 mm was noted at the distal left upper lateral cartilage adjacent to the nasal bones, with intact skin covering it.

Representative endoscopic views of the endonasal resection bed after delineation of the resection margins with the Colorado needle monopolar electrode are shown in **Figure 2**. These views illustrate the narrow pediatric endonasal working corridor and the appearance of the excision site after margin marking.

Endoscopic inspection of both the endonasal compartment and the subcutaneous dorsal dissection plane showed no macroscopically visible residual lesion and no active bleeding. The nasal cavities were irrigated bilaterally with saline. Skin closure was performed with 5-0 Vicryl. Two trimmed bilateral Reuter silicon splints were inserted and sutured with 5-0 Polysorb. A trimmed thermoplastic external nasal splint was applied over Steri-Strips, and topical antibiotic ointment was placed.

The perioperative anesthesia record documented an ASA I, 9-kg infant undergoing general anesthesia with endotracheal intubation. Airway management was uncomplicated: Mask ventilation was easy; orotracheal intubation was performed with a cuffed size 4.0 tube using a curved blade size 1; the laryngoscopic view was Cormack–Lehane grade I; and bilateral auscultation was normal. The patient was positioned supine with the neck neutral, eye protection, pressure-point protection, bilateral limb fixation, active warming, and standard monitoring.

Time-stamped intraoperative data documented entry into the operating room at 08:17, anesthetic readiness at 08:34, surgeon's arrival at 08:43, incision closure at 11:38, dressing completion at 11:42, extubation at 11:53, and departure from the operating room, awake, at 11:55. The incision-to-closure operative time was 2 h 21 min, while total operating room occupancy was 3 h 38 min. The endotracheal tube was in place from 08:39 to 11:53.

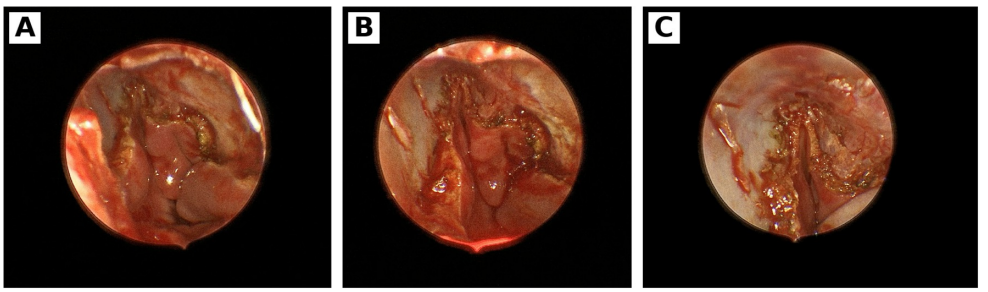


Figure 2.
Endoscopic views of the endonasal excision site after delineation of the resection margins with the Colorado needle monopolar electrode. (a–c) Representative intraoperative endoscopic views showing the resection bed and marked mucosal/periosteal margins within the narrow pediatric nasal cavity.

The anesthetic drug record included sevoflurane-based general anesthesia with propofol induction, remifentanil infusion, rocuronium neuromuscular blockade reversed with sugammadex, perioperative analgesia, dexamethasone, tranexamic acid, and antibiotic prophylaxis with cefazolin and vancomycin. No specific adverse anesthetic event was documented in the anesthesia record.

Surgery was completed successfully; no active bleeding was seen at the final endoscopic inspection, and the immediate postoperative course was uneventful. The child remained hospitalized for two nights after the primary procedure. Initial histology confirmed nasal glial heterotopia with clear margins. The Reuter splints were left in place for four weeks and then removed under general anesthesia as a day-case procedure. During this second operative session, additional histological margin specimens were obtained and were negative. Follow-up was subsequently performed every 10 to 15 days for 6 weeks. At six months, endoscopic examination showed no visible residual or recurrent lesion. A control MRI is planned at 12 months. Functionally, nasal ventilation was effective, with patency of the left naris. The aesthetic impact was moderate, with mild collapse of the left middle nasal third. Delayed reconstruction will be considered according to long-term clinical evolution.

4. Reproducible workflow for patient-specific 3D model creation

4.1 Imaging acquisition and data preparation

The workflow begins with imaging acquired as part of routine clinical care. In complex congenital nasal lesions, CT and MRI provide complementary information. The CT is particularly useful for osseous anatomy and surgical access planning, whereas MRI is essential for soft-tissue characterization and exclusion of intracranial extension. For patient-specific printing, image quality is critical. Thin-slice acquisition, minimal motion artifact, and appropriate tissue contrast improve segmentation accuracy.

For reproducibility, imaging parameters should be reported whenever available because they directly affect segmentation accuracy and model fidelity.

Imaging data were exported in DICOM format and anonymized before processing. This step is essential because reconstruction may involve clinical, technical, and educational personnel outside the immediate care team. Institutions implementing such workflows should define local procedures for data transfer, anonymization, storage, access rights, and consent for educational reuse when relevant.

4.2 Image registration and segmentation

Image processing was performed using 3D Slicer. A rigid registration was applied to align CT and MRI datasets, allowing bony anatomy from CT and the soft-tissue lesion from MRI to be visualized in a coherent spatial framework. Accurate registration is particularly important when different tissues are segmented from different imaging modalities.

Segmentation was performed using the Segment Editor module. Osseous structures were segmented from CT data, while the lesion was segmented from MRI sequences. Surrounding soft tissues were delineated to provide anatomical context. The objective was not to reproduce the entire craniofacial skeleton but to isolate the

structures relevant to surgical decision-making: nasal framework, lesion, adjacent soft tissues, and surgical access corridors.

Segmentation is one of the most expertise-dependent steps. Automatic thresholding may be useful for bone, but is often insufficient for soft-tissue lesions in small pediatric anatomy. Manual correction and clinical validation by surgeons and radiologists are therefore essential.

4.3 Model generation, mesh optimization, and slicing

Segmented structures were converted into stereolithography (STL) files and imported into Meshmixer for mesh refinement. This step included removal of artifacts, manual correction of surface irregularities, and reduction of polygon density using the Reduce function. Mesh optimization aims to balance anatomical fidelity and printability. Excessively complex meshes may generate slicing errors or prolonged processing times, whereas excessive simplification may remove clinically relevant details.

The finalized 3D Manufacturing Format (3MF) file was imported into PrusaSlicer. Slicing converts the model into printer-readable layers and allows configuration of supports, layer height, print orientation, infill, and color allocation. In this case, distinct colors were assigned to bone, soft tissue, and the lesion. Organic supports were used to maintain structural integrity during printing. Slicing should be regarded as part of the clinical workflow because model orientation and support placement influence which anatomical surfaces are visible and how easily the model can be manipulated.

4.4 Printing and validation

The model was printed at a 1:1 scale using a Prusa i3 MK3 + 3D printer equipped with an MMU3 module, using fused deposition modeling (FDM) technology. Polylactic acid (PLA) was used as the sole printing material. Three distinct PLA colors differentiated bone, soft tissues, and the lesion (**Figure 3** and **4**). Printing parameters were based on a generic PLA profile, including a 0.2 mm layer height and organic supports. The final complete model consumed 176.36 g of PLA, including support structures, and occupied the printer for approximately 22 hours. The direct PLA cost for the final successful model was approximately EUR 3, while the printer used in this workflow cost approximately EUR 800.

Fused deposition modeling was selected because it is accessible, relatively inexpensive, and suitable for rigid anatomical models. Its main limitation is material realism. The PLA provides useful spatial representation but does not reproduce mucosal texture, cartilage elasticity, vascular tissue, tumor consistency, bleeding, or dissection planes. Therefore, FDM models are particularly appropriate for anatomical orientation, planning, team briefing, and instrument compatibility assessment, but less appropriate when the objective is realistic tissue dissection. Medical 3D printing reviews consistently emphasize both the planning benefits and the need to consider cost, technical expertise, and realism [13, 14].

Before clinical use, the printed model was reviewed against the original imaging data. Validation included comparison of anatomical landmarks, lesion position, and surgical access corridors. The model was then integrated into preoperative simulation and team briefing.

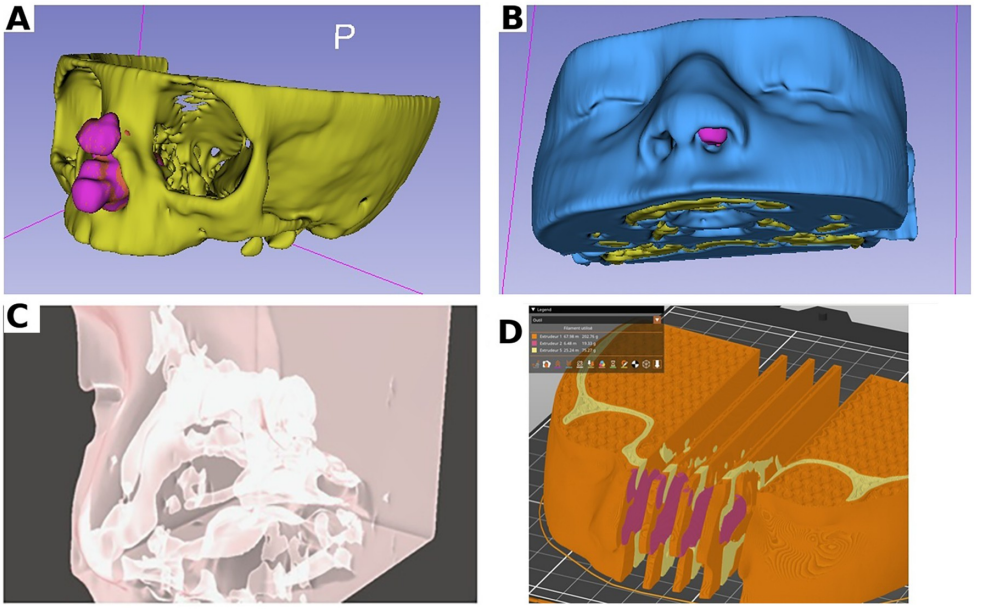


Figure 3.
3D modeling and mesh optimization workflow. (a) Patient-specific segmentation and initial 3D reconstruction of osseous structures from CT data with a superimposed lesion segmented from MRI. (b) Integration of segmented structures into a unified external anatomical model with a soft-tissue envelope. (c) Volumetric rendering of imaging data used as a reference for segmentation accuracy. (d) Slicing of the patient-specific model showing layer distribution, support structures, and multicolor PLA organization.

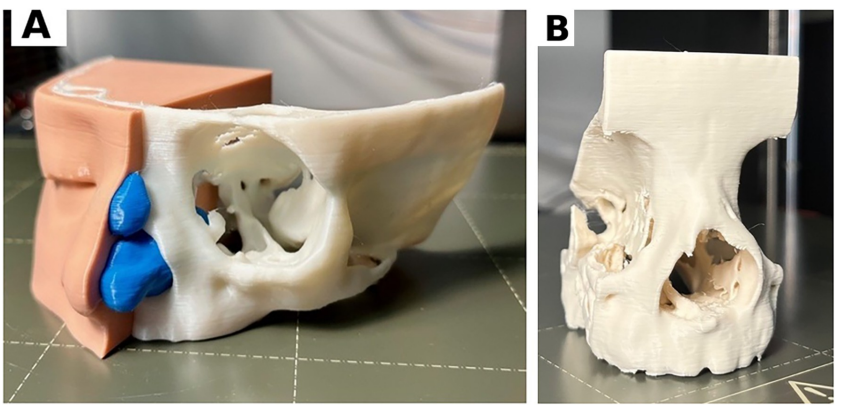


Figure 4.
Patient-specific 3D-printed anatomical model. The model was printed at a 1:1 scale using fused deposition modeling with a multicolor PLA representation. Distinct colors differentiate osseous structures, soft tissues, and the lesion, allowing visualization of their spatial relationships. The physical model was used for preoperative simulation, surgical planning, and team briefing.

5. Required resources, time, and cost considerations

A patient-specific 3D printing workflow requires imaging resources, technical software, trained personnel, printing equipment, clinical validation, and an

Workflow step	Required resources	Approximate time or key consideration	Reproducibility
Imaging acquisition	Clinically indicated CT and MRI	Routine clinical imaging; thin slices and limited motion artifacts improve segmentation	Feasible in tertiary pediatric or rhinologic centers
DICOM export and anonymization	Secure imaging export system; anonymization procedure	Required before technical or educational processing	Essential in all centers
CT-MRI registration	3D Slicer or equivalent software; trained operator	Depends on image quality and anatomical complexity	Feasible with trained personnel
Segmentation	Segment Editor module; surgeon/ radiologist validation	Approximately 2 hours after basic proficiency; longer during first implementation because of the learning curve	Reproducible but operator-dependent
Mesh optimization	Meshmixer or equivalent software	Part of approximately 5 hours for mesh optimization and slicing; artifact removal, surface correction, polygon reduction	Feasible with technical support
Slicing	PrusaSlicer or printer-specific software	Part of approximately 5 hours; determines supports; layer height; orientation; and color allocation	Printer-dependent
3D printing	FDM printer; PLA; multicolor option	Final model: 176.36 g of PLA, including supports; direct cost approximately EUR 3; printer occupancy approximately 22 hours; failed/test prints not included	Local or outsourced printing possible
Clinical validation	Review by surgeon and radiologist	Model checked against original imaging before clinical use	Mandatory before surgical planning
Simulation integration	Simulation center; briefing space; educational support	One model-based briefing of approximately 1 hour; educational reuse optional	Optimal but not strictly mandatory

Table 1.
Reproducible components, resources, and implementation requirements of the patient-specific 3D-printing workflow.

implementation framework (**Table 1**). Material costs for PLA models are generally modest compared with personnel time, segmentation expertise, software processing, and coordination between teams. In this case, once basic proficiency with the tools had been acquired, segmentation required approximately two hours, while mesh optimization and slicing required approximately five hours. The final print occupied the printer for approximately 22 hours. One model-based preoperative discussion and team briefing lasted approximately one hour. These time estimates exclude the initial learning curve, which was substantially longer during this first implementation.

The marginal direct consumable cost of the final successful model was low: 176.36 g of PLA, including supports, corresponding to approximately EUR 3. The printer itself cost approximately EUR 800. Marginal cost refers to the additional consumables needed to produce one additional model once equipment and expertise are available. By contrast, institutional cost includes staff time, coordination, equipment purchase and availability, maintenance, training, and potential

educational reuse. These indirect costs were not formally calculated in the present case. If implemented routinely, a similar patient-specific model could be produced within a maximum of one working day per case, with only a few euros' worth of PLA. This time could probably be reduced further by standardizing segmentation, mesh optimization, slicing, and printing parameters.

The workflow can be reproduced in centers without a dedicated simulation facility if they have access to imaging data, segmentation expertise, and either local or outsourced 3D printing. A minimum reproducible pathway would include Digital Imaging and Communications in Medicine (DICOM) export, anonymization, segmentation, clinical validation, and production of a 1:1 anatomical model. A simulation center pathway adds educational design, structured briefings, supervised practice, debriefing methodology, storage of reusable teaching assets, and integration into broader training programs. This distinction is important because the printed model is technically reproducible in many settings, whereas its educational value depends on how it is embedded and evaluated.

6. Simulation-supported clinical application

6.1 Operative planning and instrument compatibility

The physical model enabled hands-on exploration of patient-specific anatomy before surgery. Surgeons could examine the lesion in relation to the nasal framework, external nasal pyramid, nasal cavity, and expected access route. This supported confirmation of the combined endonasal and external approach and helped anticipate exposure, resection margins, and potential constraints related to the infant nasal cavity.

Instrument compatibility is a practical but often underestimated issue in pediatric surgery. Instruments routinely used in adults may be too large or insufficiently adapted to infant anatomy. The model allowed the surgical team to test whether selected instruments could access the target region and whether the planned approach provided adequate exposure. This type of rehearsal does not require full tissue realism; accurate geometry and scale are the critical parameters.

6.2 Team briefing and shared mental model

The model was used during a structured preoperative discussion with the surgical and perioperative team. It provided a shared reference for explaining the lesion, planned approach, expected difficulties, and key procedural steps. Shared mental models are important in complex surgery because they help team members anticipate each other's needs, recognize deviations from the plan, and respond more effectively to unexpected events.

The model also supported communication between specialties. Surgeons, anesthesiologists, nurses, radiologists, simulation specialists, and pathologists could all refer to the same physical representation rather than interpreting separate imaging views. This interdisciplinary use is consistent with current approaches to pediatric surgical simulation, which emphasize technical preparation, team-based learning, and nontechnical skills [15].

6.3 Parental counseling, pathology orientation, and education

The model was used to support the explanation of the planned procedure to the patient's parents. It should not be presented as a guarantee of surgical simplicity or absence of risk, but as a communication tool that complements clinical explanation and informed consent. For families, the tangible model may make anatomical constraints and surgical objectives more understandable than CT or MRI slices alone. Recent pediatric ENT experience suggests that 3D models may support parental understanding, satisfaction, and anxiety reduction during informed consent [16]. In the present case, however, parental comprehension and anxiety were not formally measured; future implementation should include structured feedback or teach-back assessment.

After surgical excision, specimen orientation was facilitated by the availability of a 3D anatomical reference (**Figure 5**). This illustrates that patient-specific models may have value beyond the operating room and teaching environment, including clinicopathological communication.

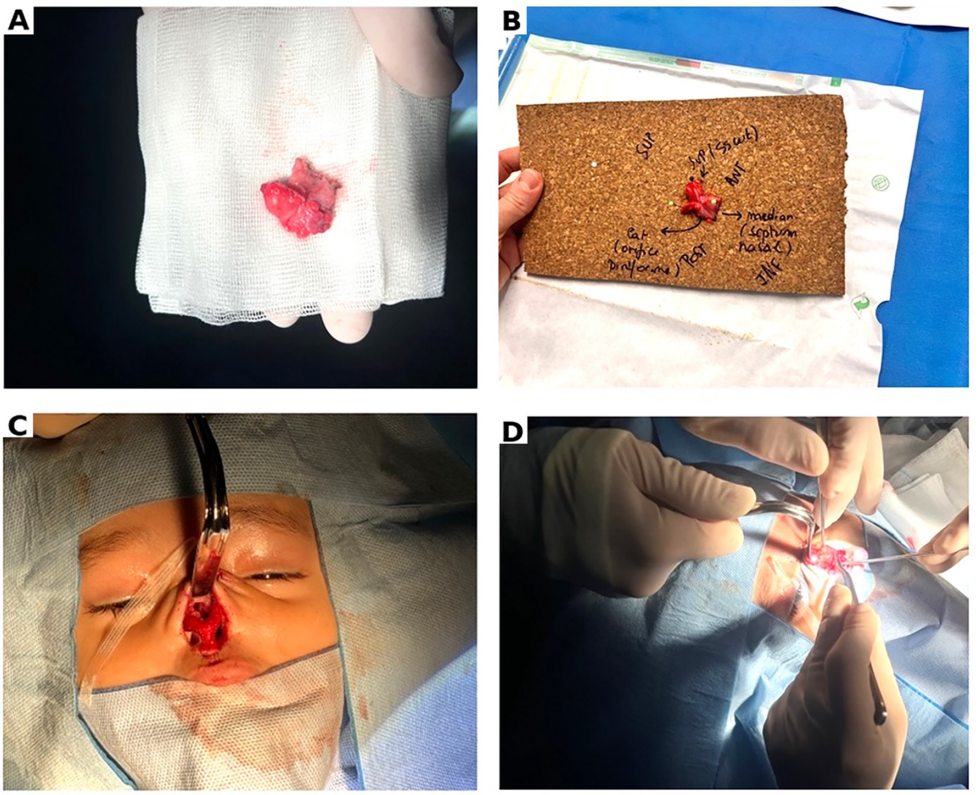


Figure 5.
Correlation between the 3D model and anonymized intraoperative findings. (a) Resected specimen. (b) Anonymized specimen orientation view after removal of potentially identifying handwritten annotations. (c–d) Cropped intraoperative views of the surgical field. The concordance between the patient-specific 3D model and intraoperative anatomy illustrates clinical correspondence between the modeling workflow and operative anatomy.

For medical students and trainees, the model created an opportunity to study a rare pediatric nasal lesion and to understand the relationship between imaging, segmentation, anatomy, surgical planning, and intraoperative findings. In medical education, 3D-printed models have been associated with improved understanding of complex anatomy, while material selection remains a key determinant of realism and educational purpose [17, 18].

7. Discussion

This case illustrates how patient-specific 3D modeling and printing can function as a simulation modality in complex pediatric nasal surgery when its objectives are explicitly defined before production. In relation to the clinical objectives stated at the outset, the model was used to improve 3D anatomical understanding, support confirmation of the combined endonasal and external approach, and check instrument compatibility within infant nasal dimensions. In relation to the communication objectives, it provided a shared visual and tactile reference for team briefing, interdisciplinary discussion, parental counseling, and pathology orientation. In relation to the educational objectives, it transformed a rare pediatric nasal lesion into a reusable teaching resource for students, residents, fellows, and the perioperative team. These benefits were perceived by the clinical team and are reported as qualitative observations; they were not measured prospectively and should therefore be interpreted as hypothesis-generating rather than as evidence of clinical or educational efficacy.

The value of the model was not limited to anatomical fidelity. Its main contribution was to create a shared interface between different forms of expertise. Radiologists contributed imaging interpretation and anatomical validation. Technically trained personnel contributed segmentation, mesh processing, and printing. Surgeons contributed clinical relevance and procedural planning. Simulation specialists contributed educational structure. Nurses, anesthesiologists, pathologists, trainees, and parents could all engage with the same object from different perspectives.

This interdisciplinarity is one of the main strengths of embedding the workflow in a simulation center. A simulation center provides physical space, educational methodology, technical support, and a culture of structured preparation and debriefing. It also helps avoid a purely technology-driven approach. The model is not valuable simply because it is printed; it is valuable because it is used with defined objectives, an explicit briefing structure, and subsequent reflection on whether those objectives were addressed.

The case also highlights the importance of selecting appropriate indications. Not every surgical case requires 3D printing. The workflow is most justified when anatomy is complex, pathology is rare, conventional imaging is difficult to mentally reconstruct, surgical risk is high, or interdisciplinary communication is particularly important. Pediatric nasal glial heterotopia meets several of these criteria: rarity, small anatomical dimensions, need to exclude intracranial extension, and requirement for precise surgical planning.

From an educational perspective, the model may help address several limitations of traditional surgical training. Rare cases are unpredictable, and trainees may not encounter them during their formal training. Even when they do, their role may be

limited by patient safety constraints. A patient-specific model allows learners to engage actively with the case, ask questions, manipulate anatomy, and rehearse reasoning before or after the operation. In this single case, however, educational benefit was inferred from feasibility and perceived usefulness rather than being measured using validated learning outcomes.

From a curriculum perspective, the workflow can be mapped to simulation-based mastery learning by defining explicit objectives, allowing deliberate practice with feedback, and setting minimum performance standards before learners participate in selected clinical tasks [19]. It can also be aligned with competency-based medical education and entrustable professional activities by translating the case into observable activities: interpreting cross-sectional imaging, identifying high-risk anatomy, selecting a surgical approach, verifying instrument compatibility, and conducting a structured preoperative briefing [20, 21]. Nontechnical objectives can be assessed with Non-Technical Skills for Surgeons (NOTSS)-style domains, including situation awareness, decision-making, communication, teamwork, and leadership during the model-based briefing [22]. This framing would allow the printed model to become one component of a structured pediatric ENT simulation curriculum, rather than an isolated educational object.

The novelty of the present workflow lies in three aspects. First, the indication is a rare pediatric rhinologic lesion, a field less frequently represented than craniofacial reconstruction or orthopedic planning. Second, the model was used not only for anatomical display; it was integrated into surgical decision-making, instrument compatibility assessment, team briefing, parental counseling, pathology orientation, and education. Third, the workflow was embedded within a university hospital simulation center, allowing the model to serve as both a clinical planning tool and a simulation-supported educational resource.

This dual clinical and educational function is important. A model created for one patient can become a reusable teaching asset once anonymized and appropriately contextualized. In rare pediatric ENT conditions, this creates educational value that extends beyond the individual case while remaining grounded in real anatomy and real clinical decision-making. Bedside or near-clinical 3D printing workflows have similarly been described as a means of connecting clinical practice, planning, and education [23].

8. Limitations

Several limitations must be acknowledged. First, this chapter is based on a single-case experience. Although the case is highly illustrative, conclusions regarding clinical outcomes, operative efficiency, complication reduction, parental understanding, or educational effectiveness cannot be generalized without further study.

Second, no quantitative outcome measures were collected. The surgical team perceived improved preparedness and reduced uncertainty, but operative time, blood loss, anesthesia duration, team performance, parental understanding, and learner outcomes were not formally compared with standard preparation. The reported benefits should therefore be considered perceived and exploratory, not proven effects of the 3D-printed model.

Third, the workflow is resource-intensive. Even when low-cost materials and accessible software are used, segmentation and validation require time and expertise.

Human resource costs may exceed material costs. Implementation, therefore, requires institutional support and appropriate case selection.

Fourth, the model depends on imaging quality and segmentation accuracy. Errors in registration, segmentation, mesh processing, or printing may produce misleading anatomical representations. Clinical validation by surgeons and radiologists is essential before using the model for decision-making.

Fifth, FDM printing with PLA provides limited material realism. The model accurately represents geometry but does not reproduce tissue elasticity, mucosal texture, cartilage behavior, bleeding, or dissection planes. Its primary value is, therefore, anatomical and strategic rather than tactile or biomechanical.

Sixth, the model was not compared with alternative planning or teaching modalities, such as imaging alone, virtual 3D reconstruction, augmented or virtual reality (VR), generic simulation models, or cadaveric dissection. Therefore, the incremental value of the printed model over these alternatives cannot be quantified from this experience.

Finally, ethical and data governance issues must be addressed. Patient-specific models are derived from identifiable clinical anatomy, even when data are anonymized. Consent, data storage, educational reuse, and publication permissions should be clearly defined.

9. Future directions

Future development should include prospective evaluation of a small number of realistic clinical and educational outcomes. Four feasible categories of objective metrics could be used. First, anatomical understanding could be evaluated using pre/post landmark-identification and spatial orientation tasks based on CT/MRI and the printed model. Second, operative planning could be assessed with a structured checklist or global rating scale covering approach selection, margin planning, and instrument compatibility. Third, technical preparation could be evaluated on endoscopic sinus or nasal simulator tasks using time, error rate, target identification, and instrument-handling metrics. Fourth, team performance during the model-based briefing could be scored with NOTSS-style communication and teamwork items or a short local briefing checklist. Parental understanding could be collected as a secondary communication outcome through teach-back or a brief satisfaction questionnaire. Mixed-methods designs combining these quantitative measures with short qualitative feedback from surgeons, trainees, parents, and perioperative staff may be particularly useful.

The workflow could also be extended to additional pediatric ENT indications, including congenital nasal masses, choanal atresia, complex septal or craniofacial deformities, pediatric skull base lesions, airway anomalies, congenital ear malformations, and revision surgery in distorted anatomy. Case selection criteria should be defined to identify situations in which 3D printing adds meaningful value.

A third direction is integration into simulation curricula. Patient-specific models could be incorporated into structured modules for residents and fellows, including presession preparation, imaging interpretation, model-based planning, procedural rehearsal, briefing, debriefing, and assessment. A progressive curriculum could expose learners first to generic models, then to virtual simulation, and finally to patient-specific models for complex cases.

The fourth direction is integration with digital technologies. Virtual reality and augmented reality overlays may complement physical models by displaying hidden structures, planned resection margins, or imaging planes. Hybrid approaches could allow learners to move between radiological images, virtual models, printed models, and operative video. Open-source DICOM-based 3D and VR modeling workflows may facilitate this development in centers with limited commercial resources [24].

Finally, future work should include cost-effectiveness analysis. Evaluation should include material costs, segmentation time, personnel costs, equipment depreciation, educational reuse, impact on operating room efficiency, and potential reduction in complications or delays.

10. Practical recommendations for implementation

Several practical recommendations can be drawn from this experience. The clinical question should be defined before printing: What decision, explanation, rehearsal, or educational objective is the model expected to support? The surgeon should be involved early in segmentation planning, because clinically irrelevant structures should not be segmented merely because they are visible, while small but surgically critical structures should be preserved.

The model should be validated against the original imaging before clinical use. Printing technology should be selected according to the objective. Rigid FDM models may be sufficient for anatomical orientation and instrument compatibility assessment, whereas more advanced materials may be required for dissection, suturing, or biomechanical simulation (**Box 1**).

Define the clinical or educational question before printing.

Confirm that imaging quality is sufficient for the intended model purpose.

Assign responsibility for segmentation, mesh processing, printing, and clinical validation.

Validate the model against the source CT/MRI before clinical or educational use.

Choose printing technology and material according to the intended use: geometry, instrument compatibility, communication, or tissue dissection realism.

Document time, consumable costs, staff involvement, failed prints, perceived impact, and, when used for education, objective trainee/team performance, using a short skills/team-briefing checklist.

Plan anonymization, consent, storage, and educational reuse before integrating the model into teaching.

Box 1.
Practical checklist for implementation.

The model should be embedded in a structured briefing or teaching session. Its value increases when it is used with defined learning objectives, supervised exploration, and debriefing. Finally, time, cost, technical difficulties, and perceived clinical or educational impact should be documented. Even simple implementation logs can support future evaluation and institutional decision-making.

11. Conclusion

Patient-specific 3D modeling and printing provide a valuable simulation-supported approach for complex pediatric nasal surgery. In the presented case of nasal glial heterotopia in a 10-month-old infant, a 1:1 printed model derived from CT and MRI data supported operative planning, instrument compatibility assessment, team briefing, parental counseling, pathology orientation, and medical education.

The workflow is reproducible using accessible software and FDM printing, although it requires technical expertise, clinical validation, and appropriate institutional organization. Its integration within a university hospital simulation center enhances its value by embedding the model into structured clinical preparation and educational activities.

The main contribution of this approach is not the printed object alone, but the creation of a shared, patient-specific simulation platform connecting imaging, surgery, education, communication, and interdisciplinary collaboration. Future work should evaluate its clinical and educational impact prospectively, define cost-effective indications, and integrate patient-specific 3D printing into broader simulation curricula for pediatric ENT and complex rhinologic surgery.

Competing Interests

The authors declare no competing interests.

Ethics statement

This chapter describes a single clinical case managed as part of routine clinical care and does not report a prospective research intervention. Formal ethics committee approval was not required for publication of this case report. Written informed consent for publication of the clinical information and images was obtained from the patient's legal guardians.

Availability of data and materials

The datasets used and/or analyzed during the development of this workflow are available from the corresponding author on reasonable request, subject to institutional data protection policies and patient confidentiality requirements.

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Author contributions

All authors contributed to the conception of the project, clinical implementation, data acquisition, technical workflow, and chapter preparation. All authors reviewed and approved the final chapter.

Author details

Mathilde Gregoire[1], Cédric Detry[2], Olivier Bouchain[1], Nicolas Peigneux[1], Alexandre Ghuysen[2], Unal Duran[3] and Florence Rogister[1*]

1 Department of Otorhinolaryngology, University Hospital of Liège, Liège, Belgium

2 SMILe Medical Simulation Center, University of Liège, Liège, Belgium

3 Department of Medical Imaging, University Hospital of Liège, Liège, Belgium

*Address all correspondence to: florence.rogister@chuliege.be

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