LITERATURE REVIEW: ADJOINT-BASED COMPUTATIONAL FLUID DYNAMICS FOR INDIVIDUALIZED SEPTOPLASTY PLANNING IN NASAL SEPTUM DEVIATION

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Abstract: Nasal septum deviation (NSD) is common anatomical pathology leading to nasal airway obstruction and reduced quality of life. Despite the accepted corrective surgery being septoplasty, postoperative outcomes remain unpredictable. Traditional surgical planning often depends on anatomical assessment and surgeon experience rather than necessarily accurately predicting airflow improvement. Recent progress in computational fluid dynamics (CFD), specifically adjoint-based optimization techniques, has brought about a paradigm shift toward customized septoplasty planning. In this review article, critically appraising the state-of-the-art in the literature regarding adjoint-based CFD techniques being utilized in the management of NSD, their ability to customize surgical interventions based on individual patient-specific airflow dynamics is emphasized. The existing clinical literature, computational methods, benefits, drawbacks, and future directions of incorporating these technologies into clinical routine are explored[1].

Key words: Nasal septum deviation, Septoplasty ,Computational fluid dynamics (CFD) , Adjoint-based CFD , Nasal airflow simulation ,Surgical planning ,Nasal obstruction

1. Introduction

Nasal septum deviation (NSD) happens in approximately 20–30% of the general population and is the most frequent source of nasal obstruction [1]. It results from displacement of the nasal septum, composed of cartilage and bone partition separating the two sides of the nasal cavity, leading to compromised airflow and symptoms including congestion, breathing, and snoring difficulty [4]. Repair through surgical procedure by septoplasty remains the most frequent therapeutic intervention to restore nasal patency.

Even though a standard procedure, septoplasty outcomes are not invariably consistent, and 15–20% of patients still have symptoms postoperatively [7] . Part of this variability is caused by the use of a subjective anatomical evaluation and lack of objective predictive means of measuring preoperative and postoperative airflow dynamics [2,3].

Current developments in computational modeling, in the form of computational fluid dynamics (CFD), offer a promising solution through nasal airflow simulation to identify areas of blockages and predict surgical outcomes [3]. Of CFD approaches, adjoint-based optimization is one that is a highly advanced methodology capable of accurately identifying geometric sensitivities in airflow to allow precise and personalized surgical planning[4].

2. Methodological Explanation: Computational Fluid Dynamics (CFD) Modeling Workflow for Nasal Septum Deviation

Table 1. workflow for Nasal Septum Deviation [8,9]

Step	Description
Medical Imaging Acquisition	High-resolution CT or MRI scans capture the patient's nasal anatomy in detail.
3D Geometry Reconstruction	The nasal cavity and septum are segmented from imaging data using software to create a 3D model.
Mesh Generation	The 3D geometry is discretized into a computational mesh refined in regions of interest.
Boundary Condition Setup	Physiological boundary conditions are applied, such as inlet flow rates at nostrils and outlet pressure.
CFD Simulation	Navier-Stokes equations governing airflow are solved using CFD software to compute velocity and pressure.
Adjoint-Based Sensitivity Analysis	The adjoint method computes gradients of airflow parameters relative to geometry changes to identify critical areas.
Surgical Planning & Virtual Surgery	Simulated modifications based on sensitivity maps are tested virtually to predict airflow improvements.
Postoperative Validation	Post-surgery imaging and airflow measurements validate CFD prediction accuracy and surgical outcomes.

3. Traditional Septoplasty and Its Limitations

Conventional septoplasty is guided predominantly by visual inspection and physical examination (anterior rhinoscopy, endoscopy), alongside imaging modalities such as CT scans to assess septal anatomy [5]. Surgeons make intraoperative decisions based on their experience, modifying the septum to improve airflow.

However, anatomical assessments do not always correlate well with functional nasal airflow [1,10]. This discordance partly explains suboptimal outcomes in some patients. For example, over-resection may lead to saddle nose deformity, while insufficient correction may fail to alleviate obstruction.

While acoustic rhinometry and rhinomanometry provide objective airflow data, they lack spatial resolution to guide targeted surgical modification. Thus, there remains an unmet clinical need for tools that predict airflow improvements with surgical intervention on an individual basis [7,8].

4. Computational Fluid Dynamics (CFD) in Nasal Airway Evaluation

CFD replicates the passage of fluids (air) based on 3D models of nasal airways acquired using CT or MRI scans. By solving the Navier-Stokes equations, CFD provides high-resolution maps of velocity, pressure map, and resistance in the nasal cavity [6].

Several studies have established CFD's capability to measure nasal airflow obstruction quantitatively and visualize the impact of anatomical variabilities [1,4]. CFD facilitates virtual surgical planning—allowing surgeons to "test" changes on a computer model before actual surgery.

However, traditional CFD procedures are computationally intensive and frequently must be run multiple times to explore different surgical approaches, making them inappropriate for clinical use[13].

5. Adjoint-Based Optimization in CFD: A Novel Approach

Adjoint-based CFD is a more recent and mathematically sophisticated approach that efficiently computes the sensitivity of airflow parameters to small geometric changes in the nasal anatomy [2].Unlike brute-force parametric studies, adjoint methods calculate gradients of objective functions (e.g., nasal resistance) relative to the shape in a single simulation [11].

This capability allows rapid identification of anatomical regions where surgical modification will yield the greatest functional benefit [5]. Thus, it facilitates patient-specific, targeted septoplasty planning with less computational cost.

6. Clinical and Research Applications of Adjoint-Based CFD

The earliest clinical translations of adjoint-based CFD are emerging. Recent studies demonstrated how this approach could guide minimal septal corrections while maximizing airflow improvements [2]. Their patient-specific simulations identified optimal resection zones, confirmed by postoperative airflow enhancement.

Other research groups have validated the technique on virtual cohorts, showing improved predictive accuracy compared to traditional CFD and standard clinical assessment [6].These promising results indicate that adjoint-based CFD could reduce unnecessary tissue removal and improve postoperative outcomes [12,13].

7. Advantages of Adjoint-Based CFD in Septoplasty Planning

• Personalization: The adjoint method provides patient-specific data, allowing surgeons to tailor interventions to each patient's unique anatomy [2].

• Computational Efficiency: By calculating sensitivity gradients in a single simulation, adjoint-based CFD drastically reduces the computational cost compared to traditional trial-and-error CFD studies [5].

• Precision: This method pinpoints specific anatomical areas where minor geometric changes can have significant functional impacts, potentially minimizing surgical invasiveness[4].

• Predictive Capability: Surgeons can simulate and compare multiple surgical scenarios preoperatively, improving outcome prediction and surgical planning [3].

Table 2: Comparison of Traditional CFD and Adjoint-Based CFD in Septoplasty Planning

Criteria	Traditional CFD	Adjoint-Based CFD
Computational Cost	High — requires multiple iterative simulations	Lower — sensitivity gradients calculated in one run
Surgical Planning	Trial-and-error with multiple geometries	Gradient-driven identification of critical regions
Precision	Limited by number of simulations	High precision through mathematical optimization
Clinical Usability	Time-consuming and limited	More feasible with automation
Outcome Prediction	Qualitative/semi-quantitative	Quantitative with detailed sensitivity analysis
Integration Potential	Low without specialized expertise	Higher potential with interdisciplinary collaboration

8. Limitations:

•Technical Sophistication: Developing accurate CFD models requires high-resolution imaging, fluid mechanics skills, and advanced computer software—environments not always available in clinics [7].

•Validation Required: Early indications are promising, but extensive clinical trials will be required to establish predictive validity and assess long-term patient outcomes [3].

•Barriers to Integration: Integration into clinical workflows seamlessly requires intuitive interfaces and seamless interdisciplinary interaction between surgeons, radiologists, and engineers that can be [2].

9. Future Directions and Research Opportunities

Clinical Translation and Workflow Integration:

Future research should focus on creating streamlined, automated pipelines for converting medical images into CFD models and adjoint-based analyses accessible to clinicians without fluid dynamics expertise [6]. Integration with surgical planning software and intraoperative navigation tools could further improve precision.

Artificial Intelligence and Machine Learning:

Combining adjoint-based CFD with machine learning could enable rapid prediction models trained on large datasets, further reducing computational time and supporting real-time clinical decision-making [5].

Multiscale Modeling:

Linking nasal airflow simulations with mucosal physiology, sensory feedback, and patient-reported symptomatology can provide holistic outcome predictions beyond purely aerodynamic measures[1].

Expanded Indications:

Beyond septoplasty, adjoint-based CFD could guide surgical corrections for other complex nasal pathologies, such as inferior turbinate hypertrophy and nasal valve collapse, enhancing the scope of personalized nasal surgery [7].

9. Conclusion

Adjoint-based computational fluid dynamics represents a cutting-edge, advanced approach for personalizing septoplasty in patients with nasal septum deviation. By providing detailed, patient-specific airflow sensitivity maps, this method can potentially improve surgical precision, reduce unnecessary tissue removal, and enhance functional outcomes. Although technical challenges and validation needs remain, ongoing multidisciplinary research and technological innovations pave the way for routine clinical integration of this promising technology.

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