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·综述·

上气道流体力学在腺样体肥大相关错𬌗畸形诊疗中的研究进展

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【摘要】 腺样体肥大是引发儿童上气道阻塞的常见病因之一，患儿往往以鼻塞为首发症状，并伴随一系列相关表现。由于鼻腔通气受阻，患儿会被迫代偿性口呼吸。口呼吸模式会改变上气道的流体环境，使气道内的流速、压力分布以及气流形态出现异常变化。长期保持口呼吸模式，会打破颌周肌群的动力平衡，进而影响颌面部的正常生长发育，并导致错𬌗畸形的发生。上气道流体力学是基于计算机流体力学技术与影像学融合发展起来的定量分析手段，能够精确描述气流在鼻腔、咽腔等复杂解剖结构中的速度、压力分布及流型特征。借助多维度流体力学参数，能够精准地描绘腺样体肥大患者上气道的流场特征，清晰呈现气道解剖结构与通气功能之间的关联，为病情的客观评估提供了一定的量化依据。在临床诊疗过程中，计算机流体力学可分析不同干预手段对气道通气状态的改善效果，对疗效进行一定的科学预判和客观评价。然而，该领域仍面临关键挑战：缺乏标准化的上气道建模与边界条件设定流程，流体力学参数与错𬌗畸形严重程度的动态演进关系尚未明确。另外，现有研究多为横断面设计而缺少纵向干预前后的流场变化数据，模拟结果向临床指标转化不足。未来，随着标准化仿真流程的建立与大样本前瞻性队列研究的开展，上气道流体力学有望结合人工智能与多模态影像，开发智能辅助诊疗系统，从而真正推动腺样体肥大及相关错𬌗畸形诊疗的科学化与个性化发展。

【关键词】 颌面生长发育；　错𬌗畸形；　口呼吸；　腺样体肥大；　计算机流体力学；　上气道；　气流特征；　个性化诊疗

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Research progress of upper airway fluid dynamics in the diagnosis and treatment of malocclusion associated with adenoid hypertrophy

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【Abstract】 Adenoid hypertrophy is one of the most common causes of upper airway obstruction in children, often presenting with nasal congestion as the initial symptom and accompanied by a series of related manifestations. Due to impaired nasal ventilation, affected children are forced into compensatory mouth breathing. This altered breathing pattern modifies the upper airway fluid environment, leading to abnormal changes in airflow velocity, pressure distribution, and flow patterns. Prolonged mouth breathing disrupts the dynamic equilibrium of perioral musculature, thereby interfering with normal maxillofacial growth and development and contributing to the occurrence of malocclusion. Upper airway fluid mechanics, developed through the integration of computational fluid dynamics (CFD) technology and medical imaging, serves as a quantitative analytical tool capable of precisely characterizing airflow velocity, pressure distribution, and flow patterns within anatomically complex structures such as the nasal cavity and pharynx. By leveraging multidi-

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mensional fluid mechanical parameters, this approach can accurately depict the flow field characteristics of the upper airway in patients with adenoid hypertrophy, clearly illustrating the relationship between airway anatomy and ventilatory function, and providing objective quantitative evidence for disease assessment. In clinical practice, CFD enables the evaluation of how different interventions improve airway ventilation, allowing scientific prediction and objective assessment of therapeutic outcomes. Nevertheless, several critical challenges remain, including the lack of standardized protocols for upper airway modeling and boundary condition definition, insufficient understanding of the dynamic relationship between fluid mechanical parameters and the progression of malocclusion severity, and the predominance of cross-sectional study designs with limited longitudinal data on pre- and post-intervention flow field changes, which restricts the translation of simulation results into actionable clinical indicators. In the future, with the establishment of standardized simulation workflows and the conduct of large-scale prospective cohort studies, upper airway fluid mechanics is expected to integrate with artificial intelligence and multimodal imaging technologies to develop intelligent decision-support systems, thereby advancing the scientific rigor and personalization of diagnosis and treatment for adenoid hypertrophy and associated malocclusion.

【Key words】 maxillofacial growth and development; malocclusion; mouth breathing; adenoid hypertrophy; computational fluid dynamics; upper airway; airflow characteristics; personalized diagnosis and treatment

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腺样体，又称咽扁桃体，位于鼻咽顶后壁中线区域，作为咽淋巴环的核心组成部分，参与儿童期呼吸道免疫防御机制的调控[1]。腺样体出生时即已存在，随年龄增长逐步增生，6~7岁达到发育峰值，青春期后因免疫功能重塑及激素水平调控发生退行性萎缩，至成人时期基本退化消失[2-3]。腺样体肥大作为儿童上气道阻塞的高发疾病，不仅会引发鼻塞、打鼾等一系列症状，更因长期口呼吸习惯对颌面部生长发育产生深远影响[4-5]，导致错𬌗畸形等严重后果[6]，严重影响儿童身心健康与生活质量[7-8]。

然而，目前该领域主要依赖影像学形态评估，难以精准量化气流动力学改变对颅颌面生长及呼吸功能的具体作用机制，导致诊疗方案缺乏个体化与精准性。近年来随着计算机流体力学（computational fluid dynamics，CFD）技术的快速发展及其与医学影像学的深度融合，上气道流体力学逐渐成为解析腺样体肥大与错𬌗畸形关联的新兴工具[9-10]。相关研究已借助多维度流体动力学参数，初步揭示气道形态改变与气流动力学特征之间的内在联系[11-12]。本文聚焦于上气道流体力学在腺样体肥大及相关错𬌗畸形诊疗中的研究与应用，系统梳理其如何为病情客观评估、个体化治疗方案制定及疗效预判提供理论依据。

1　腺样体肥大相关的错𬌗畸形

腺样体肥大引发的气道梗阻，是介导其病理改变与错𬌗畸形的核心环节。该病变所致的鼻咽部气道机械性梗阻，可引发鼻腔通气功能障碍，迫使患儿由生理性鼻呼吸模式转为代偿性口呼吸模式[13-14]。而这一呼吸模式的病理性转换，是诱发颌面部发育畸形的关键始动因素[15-16]。患者维持口呼吸，进而打破颌周肌群的生物力学平衡，触发相关肌群的适应性改建，最终影响颌面部生长发育过程[17-18]。

1.1　Ⅱ类错𬌗畸形

腺样体肥大患者中Ⅱ类错𬌗畸形的患病率较高[19]。长期口呼吸导致下颌向后下旋转[20]，下颌骨生长方向由前下转为后下，表现为下颌后缩、颏部形态异常[21]，更容易出现Ⅱ类错𬌗畸形[22-23]。同时伴随上唇短翘，上颌前牙因缺乏口轮匝肌的约束而呈现唇倾趋势[24-25]。此外，口呼吸还可导致舌位下移[26]，无法正常贴附硬腭，舌肌对上颌的生物力学作用减弱，引发颌骨内外肌力失衡，进而压迫上颌牙弓，使硬腭形成高拱型或“V”型形态，最终形成典型的“腺样体面容”[27-28]。

1.2　Ⅲ类错𬌗畸形

部分学者发现有小部分腺样体肥大患者出现Ⅲ类错𬌗畸形[29]。长期口呼吸也可导致上颌发育不足，且与腭部容积减小、尖牙间宽度缩窄、后牙反𬌗等表现密切相关[30-31]。这类患者常合并有扁桃体肥大，出现舌体前伸的代偿表现，该代偿习惯长期持续可发展为下颌前突型安氏Ⅲ类错𬌗畸形[32]。需要指出的是，颌面部生长受遗传与环境

共同调控，其中遗传因素对面部形态的构建起着主要作用[33]，因此在相关分析与干预中不应忽视个体的遗传背景。

2 腺样体肥大与上气道流体力学

2.1 计算机流体力学技术

CFD技术通过计算机和数值方法对流体力学问题进行模拟分析，近年来被广泛用于模拟呼吸系统疾病的药物输送[34-35]、分析睡眠呼吸障碍的病因和发病机制[36-37]、气道阻塞患者的气流分析[38-39]等领域。它可以根据病理、生理呼吸数据，分析气流特征，探索导致上气道塌陷的边界条件[40]。随着医学和力学等学科的紧密结合以及仿真技术的广泛应用，CFD成为了研究上气道气流动力学特征的重要手段之一[41-42]。

CFD基于锥形束CT等影像数据，重建三维上气道模型并进行体网格划分[43]。通过设定合理的边界条件（如入口流速、出口压力及壁面属性），选取适宜的湍流模型，对流场进行迭代求解[44]。最终对计算结果开展可视化呈现与定量分析，提取关键流场参数，包括气流速度分布、压力分布、壁面剪切力、鼻腔阻力、通气流量分配以及湍流动能等[38]。

该技术具有显著优势，其无创性避免了对患者的侵入性操作[45]；可重复性强，便于进行多工况对比模拟[46]；可视化效果良好，能够直观呈现气流特征[47]；同时支持“虚拟手术”模拟，有助于预测临床干预效果[48]。上述特点使其在气流动力学研究中具有重要的应用价值。

2.2 不同呼吸模式的气流特征

上气道流体力学改变与呼吸模式之间存在双向调控[49]。生理状态下的鼻呼吸过程中，气流沿鼻腔通道平稳流动，对上气道周围软硬组织施加均衡的生物力学负荷，为颌面部正常生长改建提供稳定的力学微环境[50]。而腺样体肥大引发气道狭窄后，可导致气流阻力升高、压强差增大，形成高速气流及湍流现象[51-52]。患者为了降低呼吸做功、维持机体氧供，逐步建立口呼吸的代偿模式，长期持续可发展为习惯性口呼吸[53]。一旦口呼吸模式确立，又可通过重构上气道解剖形态，加剧流体力学紊乱；下颌顺旋、舌体下移、鼻腔通气量减少及上颌骨横向发育不足[54-55]，可进一步加重气道形态异常，导致气流流速、压力分布紊乱加剧[56-57]，湍流强度与呼吸阻力同步升高，反向强化口呼吸习惯，形成恶性循环[58]。

2.3 腺样体肥大患者的气流特征

腺样体肥大患者的上气道狭窄区域可形成高速射流，其流速可达正常气道区域的2~3倍[59]。伴随局部压强降低及压力梯度形成，该区域出现气流轨迹紊乱、回流等现象[60]，湍流强度升高，最终导致气体交换效率下降、呼吸阻力增加[61]。其中鼻阈与鼻咽部为气流动力学变化最为显著的区域[62]。Hu等[63]发现气道狭窄引发的局部气流速度骤升，可使高速气流产生的剪切力相应增加，该剪切力可造成气道黏膜机械性损伤，加重局部炎症反应，进而形成“力学损伤-炎症反应-组织增生”的病理性循环[64]。

除流速与湍流异常外，压强分布异常是腺样体肥大患者气道流体力学异常的另一核心特征[65]。腺样体肥大患者上气道整体压强差明显升高，吸气期鼻腔前端至声门的压强差可达162 Pa，远高于正常儿童（30~50 Pa）[62]；同时鼻咽部存在明显压强梯度，导致气流通过时需克服更高的力学阻力，显著增加呼吸负荷[66]。这种压强异常分布不仅直接降低通气效率，还可通过力学传导作用于上气道周围组织，间接调控其生长改建过程[67]。

2.4 腺样体肥大相关错𬌗畸形患者的气流特征

腺样体肥大所引起的上气道气流改变在不同矢状向骨面型之间存在显著差异[68]。Ⅱ类错𬌗畸形患者表现出显著高于Ⅲ类错𬌗畸形患者的鼻部阻力，其口咽部可形成负压区[69]，该负压持续作用于下颌骨区域，产生舌体向后下方的牵拉效应，从而限制下颌骨前向生长。此外，较高的鼻腔阻力可能引发舌体下降，进而对下颌牙弓的横向发育产生不利影响。而Ⅲ类错𬌗畸形患者出现舌体前移，与下颌切牙唇倾及下颌前突显著相关，且此类患者常伴有舌体的显著增大[70]。

值得注意的是，随着腺样体占位率增加，硬腭所受压力方向随之发生改变[67]。轻中度肥大时硬腭受到向下的正压力，重度肥大时则转为向下的负压力。这一压力方向的改变可能影响腭部的生长发育，但其与Ⅱ类、Ⅲ类错𬌗畸形的具体关联尚需进一步研究。这提示气流动力学改变在不同骨面型的形成机制中扮演不同角色，研究这些差异对制定个体化的治疗策略具有重要意义。

3　流体力学分析在正畸治疗中的应用价值

3.1　正畸疗效评估

传统正畸疗效评估多以X线片、牙颌模型等形态学指标为核心，虽能反映牙齿与颌骨的位置关系变化，却无法量化评估气道功能的改善程度。将流体力学参数纳入正畸疗效评估体系，可弥补这一技术短板，构建“形态-功能”双重评估模式，实现对治疗效果更全面、客观的评价[71-73]。气道容积、压强差、流速分布等流体力学参数，可直接体现上气道通气功能及力学状态，为疗效评估提供量化支撑[64-65]。二者联合应用可完善正畸疗效评估体系，既能够评估牙齿排列、颌骨关系的矫正效果，又可量化气道力学环境与呼吸功能的改善程度，为治疗方案的动态调整提供全面的循证依据[74]。在精准医疗理念指导下[75]，基于流体力学参数的疗效评估体系，可推动正畸治疗从经验性矫治向精准化矫治转型，提升治疗质量与临床疗效。同时，达成“形态矫治-力学改善-功能恢复”的协同治疗目标，从而突破传统方案仅聚焦形态矫正的局限，提升多维度治疗效能[76]。

3.2　上颌牙弓狭窄

扩弓治疗是治疗牙弓狭窄、腭盖高拱的常规手段。其疗效评估已从单纯的牙弓宽度测量，深入到对上气道流体环境的分析。牙弓狭窄可导致鼻腔容积减小、气流阻力增加、流速分布不均[77-78]。采用扩弓治疗可拓宽上颌横向宽度，增大鼻腔及上气道容积，优化气流动力学分布[79-80]。临床研究证实，扩弓治疗后鼻腔横截面积平均增加10 %~15 %[41,81]，气道流速显著降低，压强分布趋于均衡，呼吸阻力显著减小[82-83]。通过流体力学模拟预判扩弓幅度与气道力学参数的关联性，可制定个体化扩弓方案，规避因扩弓不足或过度引发的气道力学环境异常。

3.3　下颌后缩

处于生长发育高峰期前后的下颌后缩患者，常使用功能矫治器前导下颌[84-85]。这种治疗方式可增加咽腔前后径，改善气道解剖形态，降低呼吸阻力[86-87]。通过模拟不同下颌前移量下的气道流体力学参数，可确定最优治疗方案[88]。这种基于力学参数的个体化方案设计，可提升治疗精准度，同步改善呼吸功能与颌面形态。在正畸治疗方案制定过程中，结合患者年龄、颌面形态特征及流体力学参数，可实现治疗方案的个体化优化，该诊疗模式既关注牙齿与颌骨的形态矫正，更重视上气道力学环境与呼吸功能的改善，通过形态与功能的协同矫治，提升治疗长期稳定性，降低错𬌗畸形复发风险。

4　研究局限

尽管流体力学分析在腺样体肥大相关研究中已取得阶段性进展，但当前研究仍存在诸多局限。样本量方面，多数研究为单中心小样本设计，且缺乏按年龄、性别、病情严重程度的分层分析，导致研究结果的代表性与外推性受限，难以形成统一的临床诊疗指南[89-91]。模型构建层面，现有研究多采用静态模型[92]，未考虑呼吸周期中软腭、舌体、腺样体等气道软组织的动态形变特性[93]，无法真实复刻生理呼吸状态下的上气道形态及流场特征[94]。此外，儿童上气道建模面临解剖结构精细、个体差异显著等挑战[95]，进一步增加了模拟的复杂性与不确定性[96]。呼吸过程中气道壁的顺应性变化、软组织的运动轨迹[97]，均会影响流体力学参数，静态模型的局限性导致模拟结果与生理状态存在偏差[98]。Li等[99]研发了简易的可变形固体与流体双向耦合作用模型，通过双向耦合作用分析了软组织与气流的相互作用，这可能弥补了CFD在气道壁、软组织方面的不足[49]。

此外，流体力学分析与正畸临床的转化衔接存在不足，且缺乏长期随访数据的支撑。现有研究多聚焦于理论模拟与短期疗效评估[100-101]，尚未建立气道流体力学参数与正畸治疗长期效果、畸形复发风险的明确联系。流体力学分析结果对正畸治疗方案的实际指导价值，仍需通过大样本、长期随访的临床研究进一步验证，以实现理论研究向临床实践的有效转化，为临床诊疗提供更可靠的循证依据。

5　小　结

腺样体肥大是儿童生长发育期高发的上呼吸道阻塞性疾病，其引发的鼻咽部气道机械性狭窄是上气道流体力学环境紊乱的核心始动因素。肥大的腺样体导致气道容积缩减、狭窄段形成，诱发气流流速升高、压强分布异常及湍流生成等一系列流体力学异常，不仅直接引发鼻塞、口呼吸、阻塞性睡眠呼吸暂停低通气综合征等临床症状，还通过改变上气道周围软硬组织的生物力学负荷，诱导上颌骨狭窄、腭盖高拱、下颌后缩，发展为错𬌗畸形（图1）。

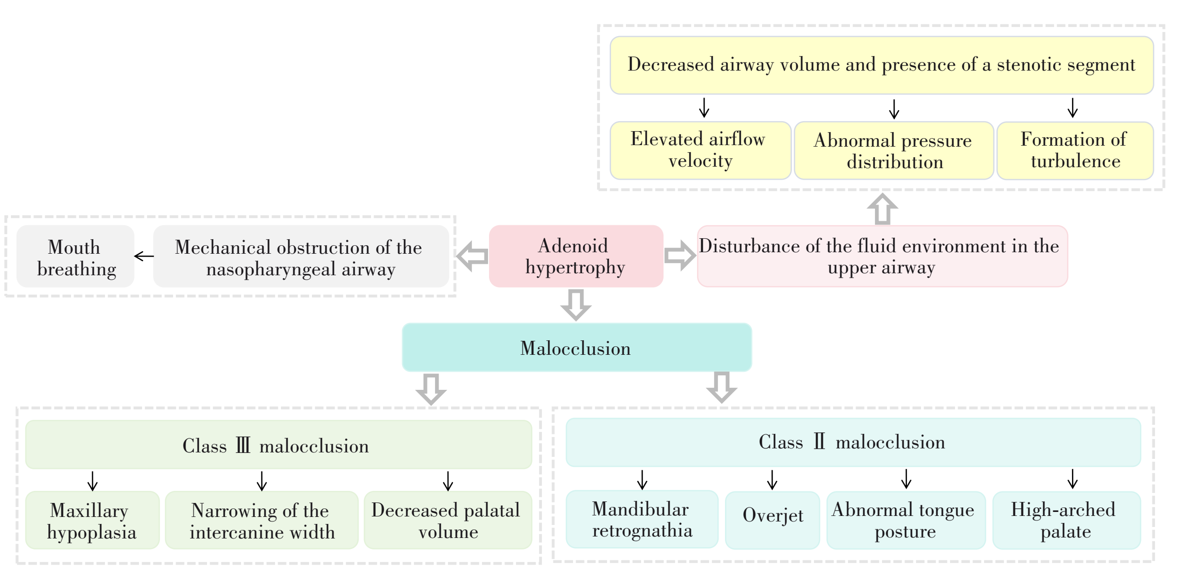

Figure 1　Adenoid hypertrophy-related malocclusion and its changes in airflow dynamics
图 1　腺样体肥大相关错𬌗畸形及其气流动力学改变

流体力学技术为阐明上述病理机制提供了全新量化视角，通过构建上气道三维几何模型，结合 CFD 精准量化气道内流速、压强、湍流强度等核心参数，明确腺样体肥大对上气道流体力学的影响规律。

口腔正畸学与 CFD 的交叉融合研究，为腺样体肥大相关错𬌗畸形的防治提供了新思路与新方法。深入开展该领域研究，可进一步阐明“腺样体肥大-流体力学紊乱-错𬌗畸形”的病理机制，提升正畸临床诊疗的精准度与临床效能，最终实现儿童上气道形态、功能与颌面部美观的协同统一，为儿童口腔健康及身心健康提供保障。

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【Ethics statement】 The authors have nothing to report.

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【Data availability statement】 Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

【Generative AI statement】 The authors declared that generative AI was not used in the creation of this manuscript.

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