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·综述·

隐形矫治器下颌前导技术治疗青少年骨性Ⅱ类错𬌗畸形的研究进展

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【摘要】 骨性Ⅱ类错𬌗畸形是青少年常见的错𬌗畸形，下颌发育不足是其主要致病机制。利用青春期生长高峰期使用功能矫治器引导下颌前伸是临床治疗的核心手段，但传统功能矫治器存在体积大、美观性差、易导致软组织损伤等不足，影响患者依从性。随着数字化技术的发展，集成了下颌前导功能（CAMA）的无托槽隐形矫治技术应运而生，兼具美观与舒适优势，为青少年骨性Ⅱ类错𬌗治疗提供了新的策略，显著提升了患者依从性。CAMA在青少年错𬌗畸形矫治中具有多维度的临床优势：①基于材料黏弹性的力学机制可优化颞下颌关节应力分布，诱导髁突生理性改建，微观上表现为骨小梁分形维数的增加；②在保证下颌骨生长量的同时，通过“𬌗垫效应”有效控制磨牙萌出，为高角型病例的垂直向控制提供了优解，且增强型精密翼设计显著提升了对下切牙的转矩控制；③改善口咽气道形态及呼吸功能，有利于患者全身健康。尽管CAMA在骨性Ⅱ类错𬌗矫治中具有重要应用价值，但目前关于其骨性与牙性效应的具体比例、长期疗效稳定性及对严重骨性不调的治疗边界等研究仍不够深入，且多为回顾性或短周期研究。未来应尽可能开展前瞻性多中心随机对照研究，构建结合人工智能辅助设计与生物力学仿真的个性化诊疗体系，综合分析颞下颌关节适应性等多种因素，进一步提高CAMA的临床应用价值。

【关键词】 隐形矫治器；　下颌前导；　功能矫治器；　生物力学；　垂直向控制；　骨性Ⅱ类错𬌗；　颞下颌关节；　骨改建；　气道形态；　牙根吸收
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Research progress on clear aligner mandibular advancement technology in the treatment of adolescent skeletal Class II malocclusion

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【Abstract】 Skeletal Class II malocclusion is a common dentofacial deformity in adolescents, primarily characterized by mandibular retrognathism. Functional appliance therapy during the pubertal growth spurt to guide mandibular advancement is considered the gold standard. However, traditional functional appliances are often associated with limitations such as bulkiness, poor esthetics, and soft tissue irritation, which can compromise patient compliance. With advancements in digital orthodontics, clear aligner technology integrated with mandibular advancement (clear aligner mandibular advancement, CAMA) has emerged as a novel strategy for treating adolescent skeletal Class II malocclusion, offering advantages in esthetics and comfort while significantly improving patient compliance. CAMA exhibits multidimensional clinical advantages in adolescent malocclusion correction: ① Its mechanical mechanism based on material visco-

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elasticity optimizes temporomandibular joint stress distribution and induces physiological condylar remodeling, microscopically manifested as increased trabecular fractal dimensions; ② While ensuring mandibular growth, it effectively controls molar eruption through the "bite block effect," providing an optimal solution for vertical control in high-angle cases, and the enhanced precision wing design significantly improves torque control of lower incisors; ③ It improves oropharyngeal airway morphology and respiratory function, benefiting patients′ overall health. Although CAMA holds significant value in treating skeletal Class II malocclusion, current research remains insufficient regarding the specific proportions of skeletal versus dental effects, long-term stability of treatment outcomes, and therapeutic boundaries for severe skeletal discrepancies, with most studies being retrospective or short-term. Future research should prioritize prospective multicenter randomized controlled trials, establish personalized diagnostic and treatment systems integrating artificial intelligence-assisted design and biomechanical simulation, and comprehensively analyze multiple factors including temporomandibular joint adaptability to further enhance the clinical value of CAMA.

【Key words】 clear aligner; mandibular advancement; functional appliance; biomechanics; vertical control; skeletal Class II malocclusion; temporomandibular joint; bone remodeling; airway morphology; root resorption

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骨性Ⅱ类错𬌗畸形是青少年正畸临床中最常见的错𬌗畸形之一，其核心病理机制为下颌骨发育不足，而非单纯的上颌发育过度[1-2]。流行病学结果提示，该类畸形的患病率约为19.56%，不仅严重影响患者的颜面侧貌美观，还常伴发气道狭窄及咀嚼功能异常[1]。研究发现，利用青春期生长高峰期进行功能矫形治疗，通过诱导髁突软骨增殖及关节窝改建，从而获得最佳的骨骼矫治效应[3-4]。

长期以来，Twin-block、Herbst等传统功能矫治器被视为治疗的核心手段。然而，此类装置体积庞大且构造复杂，常导致患者出现语音不清、软组织压痛及咀嚼困难等不良体验[5]。青春期患者对自身形象及社会评价极为敏感，传统矫治器的可见性极易引发社交焦虑，导致患者的生活质量下降及佩戴依从性不足，进而削弱治疗效果[6-8]。与此同时，随着社交媒体的广泛传播，青少年及家长对正畸治疗的审美要求日益提升，对隐形矫治及舒适化治疗的关注度呈现显著上升趋势[9-11]。

在此背景下，集成了下颌前导功能（clear aligner mandibular advancement，CAMA）的无托槽隐形矫治技术应运而生。该技术突破了早期隐形矫治仅能处理简单牙性移动的局限，通过精密翼或改良式𬌗垫设计，将下颌导向功能与数字化排齐技术有机融合[12-14]。相较于传统装置，CAMA在美观性、舒适度及口腔卫生维护方面具有显著优势，且随着材料学的进步，新型3D打印树脂及形状记忆高分子材料的应用，进一步提升了矫治器的力学性能与固位力[15-18]。

尽管CAMA技术在临床上已得到广泛应用，但其骨性改建的真实效能仍存在诸多争议[19]。一方面，系统评价指出CAMA能有效改善Ⅱ类矢状向关系，其疗效与固定功能矫治器相当[20-21]；另一方面，关于其治疗结果中骨性效应与牙性代偿的确切比例、长期稳定性、潜在风险（如牙根吸收、后牙开𬌗等）以及不同垂直骨面型患者的适应证边界，目前尚无定论[22-23]。此外，隐形矫治高度依赖患者依从性的特点，以及数字化设计预测值与临床实际达成度之间的偏差，也对正畸医生的临床决策提出了新的挑战[24-26]。鉴于此，本文拟对CAMA的装置设计原理、生物力学机制、材料学进展及临床多维度疗效进行综述，旨在为临床提供更为科学、精准的诊疗依据。

1　隐形矫治器下颌前导装置的分类与设计原理

隐形矫治器已突破单纯牙齿移动的范畴，发展为集牙齿矫治与颌骨矫形于一体的综合系统。其设计原理的核心在于通过特定的结构设计，将下颌维持在功能性前伸位，从而在颞下颌关节处产生改建所需的生物力学信号。传统隐形矫治器主要依赖热压膜工艺，但该工艺在拉伸过程中会导致材料厚度分布不均，进而影响矫治力的精准表达。研究表明，热压膜后的矫治器在磨牙及𬌗垫区域厚度显著变薄，且与牙齿表面存在不规则间隙，这可能导致施力效率下降[27-28]。

为克服这一局限，学者尝试使用直接3D打印技术和形状记忆高分子材料。相较于传统聚对苯二甲酸乙二醇酯-1，4-环己烷二甲醇酯（polyethylene terephthalate-1，4-cyclohexanedimethylene tere-

phthalate，PETG）材料，基于数字光处理工艺打印的矫治器具有各向异性的力学特性，能通过数字化设计在特定区域局部增厚以提高刚度[29-30]。4D打印材料具备对温度敏感的形状记忆功能，在口腔环境下能抵抗长期的循环加载疲劳，维持更恒定且持久的矫形力，显著减少了因材料应力松弛导致的力值衰减[31-33]。

根据制造工艺、导下颌部件的空间位置及辅助机制的差异，目前临床主流的隐形前导矫治装置可分为以下几类。

1.1　翼状导下颌装置

以Invisalign®系统的下颌前导功能为典型代表。其核心设计是在上颌矫治器磨牙颊侧和下颌矫治器前磨牙颊侧构建成对的精密翼。当患者闭口时，下颌翼远中斜面与上颌翼近中斜面主动锁结，迫使下颌向前滑移。Durmus等[34]2025年的有限元分析显示，翼状装置构建了动态的力学传导系统。与刚性的双阻板矫治器（Twin-block矫治器）不同，隐形材料的黏弹特性使得Von Mises应力峰值虽集中在精密翼连接处，但能通过全牙列包裹将反作用力有效分散，避免单颗牙齿牙周膜应力过载。此外，Ray等[35]指出，不同品牌材料的吸水性与老化性能差异会直接影响精密翼的耐磨耗性，进而影响下颌前导位置的维持稳定性。

1.2　阻挡/聆垫类装置

此类装置的设计灵感源自Twin-block，通过在矫治器聆面构建70°的树脂聆垫引导下颌。与翼状装置相比，其独特优势在于垂直向控制。Tosun等[36]研究表明，通过数字化调节后牙聆垫的厚度，可以产生显著的压入效应，有效限制后牙萌出，防止下颌顺时针旋转，尤其适用于高角病例。Su等[37]进一步探讨了边缘设计对聆垫装置生物力学性能的影响，发现采用扇形边缘虽美观，但在高负载下易发生脱位；而高位直线型边缘配合优化附件，能显著提升矫治器在复杂功能运动中的固位力与施力效率。

1.3　牵引辅助与混合设计

为解决复杂病例中矫治器固位不足或支抗丧失的问题，临床设计趋向于混合化。附件作为隐形矫治的把手，其几何形态至关重要。体外研究证实，优化形状的复合树脂附件能显著提升剪切抗力[38-39]。研究者评估了不同树脂材料及粘接技术对附件耐久性的影响，建议使用高填料含量的复合树脂以减少磨损[40-41]。此外，针对严重骨性差异，Yamaguchi-Higuchi等[42]提出了结合微种植钉的混合锚抗策略。通过在后牙区植入微钉施加额外的压低或远中移动力，有效抵消下颌前伸产生的下切牙唇倾副作用。Ye等[43]报道的病例更展示了将前方牵引面具与隐形矫治器结合，成功矫治骨性Ⅲ类伴严重反聆的潜力。为确保这些复杂设计的临床精准实施，研究者强调了高精度口内扫描及3D打印间接粘接托盘的重要性，研究显示打印方向与层厚参数对附件转移精度有显著影响[44-46]。

2　隐形矫治器下颌前导技术诱导骨改建与优化生物力学机制

隐形矫治器下颌前导技术不仅是颌位的机械重定位，更是一个涉及骨骼、肌肉及牙周组织的复杂生物力学重塑过程。其核心机制在于通过改变下颌的空间位置，构建全新的口颌系统应力场，进而诱导颞下颌关节的适应性改建及神经肌肉系统的功能重编程。系统综述指出，隐形矫治器对颞下颌关节的长期影响虽总体温和，但其生物力学传导效率高度依赖于材料特性与咬合设计的协同作用[47]。

2.1　颞下颌关节的应力分布特征

有限元分析是揭示隐形矫治力学传导机制的关键工具。传统的静态有限元分析往往忽略了牙齿移动过程中的非线性变化，而近年提出的迭代宏-微循环动态仿真模型显示，隐形矫治器在长期佩戴中，其应力分布会随着牙齿的位移发生显著迁移[48]。研究表明，CAMA通过全牙列包裹设计，将下颌前伸产生的反作用力均匀分散至整个牙弓，使关节盘及髁突表面的Von Mises应力分布较传统刚性矫治器更为均匀，有效规避了局部压应力过大引发的软骨退行性变风险[49]。针对不同移动模式的力学模拟发现，当配合磨牙远中移动时，矫治器在牙槽骨界面产生的应力主要集中在颈缘区域，而合理的附件设计能将这种应力向根尖方向传导，从而刺激骨皮质的改建与新骨沉积[50]。正畸驱动的骨发生理论进一步佐证了这一点，即适度的张应力环境能激活牙槽骨的成骨潜能，为下颌骨在矢状向的生长提供结构基础[51]。对比不同的分步移动策略发现，蛙跳式移动比连续移动更能给予骨组织足够的应力弛豫时间，有利于维持骨改建的代谢平衡[52]。

2.2　神经肌肉系统的功能适应

骨骼形态的改建往往继发于神经肌肉功能的适应性改变。表面肌电图研究显示，矫治器植入

初期会显著改变咀嚼肌的肌电活动模式，尤其是咬肌和颞肌的协同收缩能力增强[53]。这种改变在引入矫垫或精密翼后更为明显。对照研究证实，后牙区的咬合抬高装置能诱发高张力肌电反应，迫使下颌寻找新的前伸稳定位，从而通过肌肉-肌腱-骨膜的力学传递链刺激髁突生长中心[54]。与传统大体积矫治器常导致肌肉疲劳不同，隐形矫治器较小的垂直打开量使升颌肌群处于更适宜的生理拉伸范围，既能产生持续的矫形力，又避免了因过度牵张引发的肌肉痉挛或疼痛[8]。此外，微振动装置在隐形矫治中的辅助作用显示，机械振动可能通过改善局部血流和代谢，进一步促进神经肌肉系统对新颌位的适应[55]。

2.3　牙齿移动的生物力学边界与牙根应力

在前导下颌的同时，隐形矫治器还需完成复杂的牙齿移动，这一过程伴随着潜在的生物力学风险。回顾性研究指出，在治疗深覆矫伴Ⅱ类错矫时，利用隐形矫治器压低切牙的效率约为52.2%，且过大的压低力易导致根尖应力集中[56-57]。更为关键的是牙根吸收的风险。系统评价及随机对照试验均表明，虽然隐形矫治器总体上的牙根吸收风险低于固定矫治器，但在进行大幅度转矩控制或压低移动时，牙根表面的应力集中仍不容忽视[58-59]。特别是当矫治力与咬合力叠加时，牙周膜内的流体静压力可能超过毛细血管灌注压，导致无菌性坏死。三维有限元分析建议，在设计上前牙转矩时，应采用优化的附件几何形态以平滑应力峰值[60]。此外，数字化设计应充分考虑牙根在牙槽骨内的解剖边界，避免因过度扩弓或倾斜移动导致骨开裂或骨开窗，这对于保障CAMA治疗的牙周安全性至关重要[61-63]。

3　隐形矫治器下颌前导技术的临床疗效的多维度评价

随着隐形矫治器下颌前导技术的普及，对其疗效的评价已不再局限于单一的头影测量分析，而是建立起涵盖骨性/牙性效应、气道功能、牙周安全性及长期稳定性等在内的多维度评价体系。

3.1　骨性效应与牙性代偿的占比

在骨性Ⅱ类错矫畸形的矫治中，能否最大程度地利用下颌生长潜力并有效控制下切牙的唇倾代偿，是衡量矫治器效能的核心指标。对照研究证实，CAMA治疗后蝶鞍点-鼻根点-下齿槽座点角（Sella-Nasion-B point angle，SNB）显著增加、上齿槽座点-鼻根点-下齿槽座点角（A point-Nasion-B point angle，ANB）减小，其诱导的下颌升支高度增长与固定功能矫治器相当，表明其具有实质性的骨骼改建能力[64]。最新对比研究也发现，Invisalign下颌前导在改善颌骨矢状向关系方面与Twin-block无统计学差异，但在控制下切牙唇倾方面表现更佳（牙性代偿量较Twin-block组减少2.0°~3.0°）[65]。

垂直向控制是CAMA的另一大优势，尤其对于伴有深覆矫的病例。随机临床试验（ClinicalTrials.gov registration：NCT06609733）显示，CAMA组在纠正深覆矫时的平均疗程显著短于固定矫治组（平均缩短3~5个月），且患者满意度更高[66]。这得益于隐形矫治器对牙齿的垂直向控制机制，即通过前牙区的压低和后牙区的萌出控制来实现咬合打开。回顾性研究指出，CAMA对下切牙的压低效率约为52.2%，配合下颌前导产生的矫垫效应，能有效防止下颌发生顺时针旋转，这对高角病例的面型保护至关重要[56-57]。然而，在处理Class II亚类病例时，单侧导下颌的牙性代偿（如中线偏斜矫正不全）仍是临床难点，需配合更精细的附件设计[67]。此外，三维分析强调，在进行大范围牙齿移动时，需警惕切牙转矩控制不足导致的骨开窗风险[63,68]。

3.2　气道形态与呼吸功能的改善

下颌后缩是导致上气道狭窄及阻塞性睡眠呼吸暂停的常见解剖因素。CAMA通过前导下颌，能直接扩大咽腔容积。系统综述及病例报告证实，CAMA治疗后，患者的上气道最小横截面积显著增加（平均增加130~180 mm^2），呼吸暂停低通气指数降低，血氧饱和度升高，这对改善青少年的通气功能及预防成人期阻塞性睡眠呼吸暂停具有重要意义[69-70]。影像学分析进一步细化了这一改变：治疗后口咽及喉咽部的体积增加最为显著（体积增量为15%~20%，或平均增加3 000~4 000 mm^3），舌骨位置向前下方移动；且与Twin-block相比，CAMA在维持气道通畅的同时，因其体积较小，对舌体占据口腔空间的干扰更小，有利于舌位的正常化[71-72]。这种气道改善与下颌前导量呈正相关，且在生长发育高峰期介入治疗能获得更稳定的气道形态学适应[73]。

3.3　牙周健康与牙根安全性的评估

相较于固定矫治器，CAMA在维护牙周健康方面具有天然优势。临床试验（ClinicalTrials.gov reg-

istration：NCT06858033）表明，CAMA组患者的牙菌斑指数和牙龈指数显著低于固定矫治组（平均指数评分低0.5~0.8），且龈沟液中的白细胞介素-1β等炎性因子水平更低[74-75]。微生态学研究揭示，隐形矫治器较少改变口腔菌群的多样性，红色复合体等牙周致病菌的检出率较低[76-77]。此外，配合益生菌制剂使用可进一步降低CAMA治疗期间的牙龈炎发生率[78]。

在牙根安全性方面，Meta分析及系统评价均显示，隐形矫治器引起的牙根吸收发生率及严重程度总体低于固定矫治器（重度吸收发生率降低30%~40%）[58,62]。这可能归因于其矫治力更为间断和柔和。然而，利用人工智能（artificial intelligence，AI）辅助的锥形束CT（cone beam CT，CBCT）分析指出，在进行大幅度压低或转矩移动（如上前牙内收）时，CAMA仍可能导致切牙根尖的显著吸收[59]。建议在设计大范围牙齿移动时，应充分评估牙根与皮质骨的解剖关系，避免因牙根接触骨皮质而加重吸收风险[60-61]。

3.4　治疗阶段性与长期稳定性

CAMA具备同步矫治优势，可在下颌前导的同时进行牙列排齐。然而，数字化设计的预测值与临床实际达成度之间往往存在偏差。研究发现，牙弓宽度的扩展，特别是前磨牙区，具有较高的可预测性（准确度通常可达70%~80%），但在拔牙病例中，尖牙远移和牙根平行度的实现率往往低于预期，常需额外的精细调整阶段[79-80]。

三维有限元分析进一步指出，在不同牙列阶段进行扩弓时，隐形矫治器的力学表达存在差异，建议在混合牙列期扩弓时应设计过矫治以抵消材料的弹性形变[80]。针对磨牙远移的支抗控制，力学模拟发现单纯依靠矫治器包裹进行远移会导致前牙明显的唇倾副作用，建议配合Ⅱ类牵引或骨钉以增强后牙支抗的稳定性[81]。对于自制或院内加工的隐形矫治器，研究表明其在处理简单排齐时效率较高，但对于复杂的下颌前导和咬合重建，其精度和材料耐久性仍不如商业化系统，需谨慎选择适应证[82]。

关于旋转控制，系统综述指出，对于圆柱形牙齿（如前磨牙）的旋转矫治，CAMA的效率较低，需依赖优化的附件系统（若无优化附件，效率常低于40%）[83]。利用数字化技术进行过矫治设计是弥补这一缺陷的关键[25]。尽管如此，长期随访研究证实，只要遵循严格的适应证选择和依从性管理，CAMA治疗后获得的咬合关系和骨骼改建在保持期内表现出良好的稳定性，未见明显的复发趋势[23]。

3.5　潜在风险与并发症

尽管CAMA优势显著，但临床应用中仍需警惕其特有的潜在风险。首先是后牙开𬌗问题，由于矫治器材料厚度（通常单层0.75 mm）产生的压入效应，部分患者在治疗结束后可能出现后牙接触不良，往往需要额外的精细调整阶段[26]。其次是牙根吸收风险，利用AI辅助CBCT分析发现，在进行大幅度上前牙内收或压低时，约10%的病例可能出现中度以上的根尖吸收，提示对于需大量牙齿移动的病例应慎重评估[59]。此外，医源性釉质损伤也是不容忽视的问题。对比不同去附件工具对釉质表面的影响发现，使用高速钨钢车针虽然效率高，但易产生肉眼不可见的微裂纹，建议临床采用多步抛光系统以恢复釉质的微观完整性[84]。长期佩戴造成的微塑料释放等生物安全性问题也逐渐引起关注[85-86]。

4　局限性与展望

4.1　局限性

尽管CAMA在临床应用中优势显著，但仍面临诸多制约。首先，生物安全性问题值得关注。隐形材料在长期磨损中可能释放微塑料、纳米塑料及微量双酚A，存在潜在健康风险[85-86]，且3D打印光聚合树脂中残留单体的细胞毒性亦不容忽视[87]。其次，材料性能衰减影响矫治效能。矫治器的力值输出与尺寸稳定性会随周期性摘戴而显著衰减[88]，且材料易受饮食色素浸染影响美观[89-90]。若采用不当的机械刷洗，不仅难以彻底除色，还会加剧表面粗糙化与菌斑附着[91-92]。最后，社会与环境负担日益凸显。社交媒体上泛滥的非专业夸大宣传极易误导患者的治疗预期[9,11]；同时，大量废弃塑料矫治器引发了严峻的医疗环保难题，亟待建立有效的降解回收机制[93]。

4.2　未来展望

CAMA未来的演进核心将由“数字化排齐”转向“生物力学驱动的骨改建”。人工智能在牙齿自动分割与排牙中的精度已接近专家水平[44]，未来结合牙根吸收生化标志物监测[94]及分形维数分析的微观骨改建评估[95]，有望构建出生物与力学双重反馈的智能诊疗系统。同时，其适应证正大幅拓展，已逐步应用于唇腭裂序列治疗及正颌手术术后固定[96-97]。在微种植钉等辅助下，CAMA已成

功攻克成人骨性Ⅲ类代偿及阻生牙牵引等复杂病例[98-99]，并能与微创修复相整合，实现美学功能双重重建[100]。最终，CAMA有望升级为集诊断、监测与治疗于一体的数字化口颌健康管理平台。

5　小　结

CAMA核心优势体现在以下3个方面。①生物力学机制的优化：利用高分子材料的黏弹性缓冲咬合力，使颞下颌关节受力更均匀，诱导髁突产生更趋于生理性的改建，这已通过骨小梁分形维数的增加得到微观验证；②垂直向控制的增强：通过矫治器的“殆垫效应”压低后牙，有效防止下颌顺时针旋转，为高角及垂直生长型患者提供了优于传统装置的治疗选择；③多维度的临床获益：在改善面部侧貌的同时，显著提升了上气道通气容积，且因其美观舒适的特性极大地提高了患者依从性。然而，CAMA并非万能，其对严重骨性不调的矫治极限、牙根在复杂移动中的安全性以及长期疗效的稳定性仍需持续关注。未来，随着4D打印记忆材料的应用、人工智能辅助的精准预测以及口腔微生态监控的引入，CAMA有望实现从“经验驱动”向“数据与生物学驱动”的精准诊疗跨越（图1）。

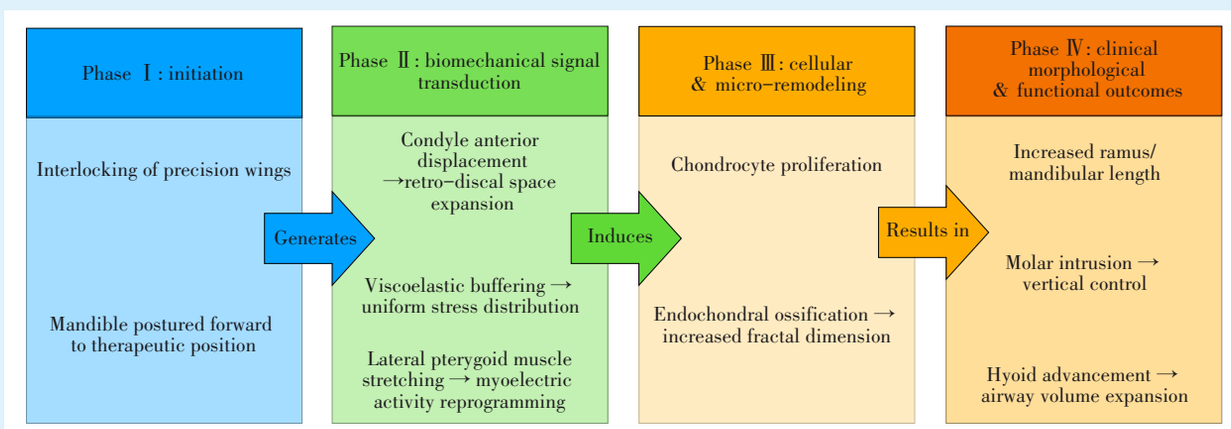

Figure 1　Overview of the biomechanical mechanisms of stomatognathic system remodeling induced by clear aligner mandibular advancement

图1　隐形矫治器下颌前导诱导口颌系统改建的生物力学机制概述

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