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·临床研究·

基于CT设计靶向翼外肌导航导板的临床应用

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【摘要】 **目的** 探讨靶向翼外肌上头和下头的口外导板系统对提升颞下颌关节盘前移位和翼外肌疼痛注射治疗的精准性，为临床精准治疗提供参考。**方法** 获得单位医学伦理委员会审查批准，并获得患者知情同意，对7例关节盘前移位伴或不伴翼外肌疼痛患者拍摄螺旋CT采集颅面数据，经Mimics 21.0软件重建颅面部三维结构，确定翼外肌上头及下头附着点，并设计双注射路径和固位系统，使用数字光处理技术3D打印个性化导板。患者在导板引导下进行单次靶向翼外肌上头和/或下头注射肉毒杆菌毒素A(botulinum toxin type A，BTX-A)20 U BTX-A治疗，术中即刻行CT扫描，与术前设计比较验证注射精度，并于术后3天、术后1、2、4周使用视觉模拟评分(visual analogue scale，VAS)对疼痛进行评分；在术后2周和4周记录关节弹响改善情况，同时监测并发症。**结果** 共对7例患者15个注射位点在导板引导下进行翼外肌上头/下头注射。导板引导下所有注射的角度偏差均控制在2.5°以内，分别为上头2.49°±0.17°，下头2.31°±0.16°，针尖距离偏差均在2 mm内，上头为(1.96±0.25)mm，下头为(1.65±0.21)mm；疼痛显著改善率(VAS评分下降≥3分)从术后3 d的60%(9/15)提升至术后2周的85%(13/15)，术后4周维持86.7%(13/15)；关节弹响改善率在术后2周为72%(11/15)，术后4周稳定在75%(11/15)；仅观察到1例注射位点的肿胀，1例短暂的感觉异常，短期内自行恢复，未发生神经血管损伤事件。**结论** CT引导下导板通过精准分靶设计使翼外肌注射误差小，临床效果较好且安全性良好，可为颞下颌关节紊乱病提供解剖特异性强、操作普适性高的靶向治疗方案。

【关键词】 CT引导； 计算机辅助设计； 3D打印； 口外导板； 翼外肌； 精准注射； 肉毒杆菌毒素A； 颞下颌关节紊乱病； 关节盘前移位； 翼外肌疼痛

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Clinical application of a CT-designed guide plate for targeted injection into the lateral pterygoid muscle

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【Abstract】 **Objective** To investigate the effectiveness of an extraoral guide plate system targeting the superior and inferior heads of the lateral pterygoid muscle in improving the accuracy of injection therapy for anterior disc displacement (ADD) of the temporomandibular joint (TMJ) with lateral pterygoid myalgia, and to provide a reference for precise clinical treatment. **Methods** With approval from the institutional medical ethics committee and informed consent from patients, spiral CT scans were performed on seven patients with ADD accompanied or not accompanied by lateral ptery-

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goid myalgia to acquire craniofacial data. Mimics 21.0 software was used to reconstruct three-dimensional craniofacial structures, identify attachment points of the superior and inferior heads of the lateral pterygoid muscle, and design dual injection paths along with a retention system. Personalized templates were fabricated using digital light procession-based 3D printing. Under the guide plate, a single targeted injection of 20 U of botulinum toxin type A (BTX-A) was administered into both the superior and/or inferior heads of the lateral pterygoid muscle. Immediate postoperative CT scans were conducted to compare actual needle placement with preoperative plans. Pain was assessed using the visual analogue scale (VAS) at 3 days and 1, 2, and 4 weeks postoperatively. Joint clicking was recorded at 2 and 4 weeks, and complications were monitored throughout the duration of the study. **Results** A total of 15 sites in 7 patients were injected into the upper / lower head of the lateral pterygoid muscle under the guidance of the guide plate. Under the guide plate, all of the injections achieved an angular deviation within 2.5° (superior head: 2.49° ± 0.17°, inferior head: 2.31° ± 0.16°) and a needle tip positional deviation within 2 mm [superior head: (1.96 ± 0.25) mm, inferior head: (1.65 ± 0.21) mm]. The significant pain improvement rate (defined as ≥3-point reduction in VAS score) increased from 60% (9/15) at day 3 to 85% (13/15) at 2 weeks post-operation, stabilizing at 86.7% (13/15) at 4 weeks post-operation. Joint clicking improvement rates reached 72% (11/15) at 2 weeks post-operation and 75% (11/15) at 4 weeks post-operation. Regarding safety, only one case of injection site swelling and one case of transient paresthesia were observed; both resolved spontaneously within a short period of time. No neurovascular injury events occurred. **Conclusion** CT-guided guide plate achieves precise targeting design to minimize injection errors in the lateral pterygoid muscle. This technology is effective and safe, and it can provide an anatomically specific and operationally versatile targeted therapy for temporomandibular disorders.

【**Key words**】 CT guidance; computer aided design; 3D printing; extraoral guide plate; lateral pterygoid muscle; precise injection; botulinum toxin A; temporomandibular joint disorder; joint disc anterior displacement; pain of lateral pterygoid muscle

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颞下颌关节紊乱病(temporomandibular disorders,TMD)以颞下颌关节及咀嚼肌系统功能障碍、疼痛为核心特征。流行病学研究显示TMD全球患病率达6% ~ 9%[1],发病率高居肌肉骨骼疾病的第二位,人群症状检出率更达40% ~ 80%[2-3]。TMD不仅造成患者颌面部功能障碍等,还会并发吞咽障碍及心理问题,影响生活质量[4];对于青少年患者,TMD甚至还可导致下颌骨发育异常,引发面部不对称、下颌后缩等颅面畸形,继而影响气道功能和睡眠质量[2]。在TMD的多种亚型中,关节盘前移位(anterior disc displacement,ADD)与咀嚼肌疼痛占比最高[2]。从发病机制上看,ADD和翼外肌疼痛与翼外肌(lateral pterygoid muscle)功能紊乱密切相关[5-6]。磁共振成像(magnetic resonance imaging,MRI)研究证实,当翼外肌上头仅附着于关节盘时,ADD发生风险显著增加[7];而翼外肌痉挛不仅可诱发ADD,翼外肌的退行性变可进一步加重ADD程度[8]。同时,翼外肌触诊压痛是TMD的常见体征,且翼外肌功能紊乱常与肌功能异常及关节力学改变形成恶性循环[9]。

针对翼外肌功能障碍,肉毒杆菌毒素A型(botulinum toxin type-A,BTX-A)注射已被证明是有效的干预手段。BTX-A通过特异性裂解突触前膜25 kDa突触关联蛋白(synaptosomal associated protein 25 kDa,SNAP-25),抑制乙酰胆碱释放并阻断钙通道活化,从而产生剂量依赖性的肌肉松弛效应[10]。临床研究证实BTX-A注射疗法可用于颌面部疾病和TMD的治疗[11-12],翼外肌等长训练也被推荐为ADD的补充疗法[3,13]。然而,翼外肌的BTX-A注射面临严峻技术挑战,首先,翼外肌位于面深部颞下窝,毗邻上颌动脉和下颌神经等重要结构,传统盲法注射易导致血管神经损伤;颞下窝空间狭窄与缺乏可视化手段,使术者难以区分附着于蝶骨颞下嵴的翼外肌上头和起自翼外板的翼外肌下头;

更严重的是，依赖主观经验的注射方式定位误差率高达35%，直接导致疗效不稳定及并发症风险[14]。

本研究设计一种CT三维重建与计算机辅助设计（computer-aided design，CAD）支持的口外导板系统，旨在实现翼外肌上/下头的精准解剖定位，建立规避神经血管风险的标准化注射路径，最终提升BTX-A治疗ADD及肌源性疼痛的安全性与临床疗效稳定性。

1　资料和方法

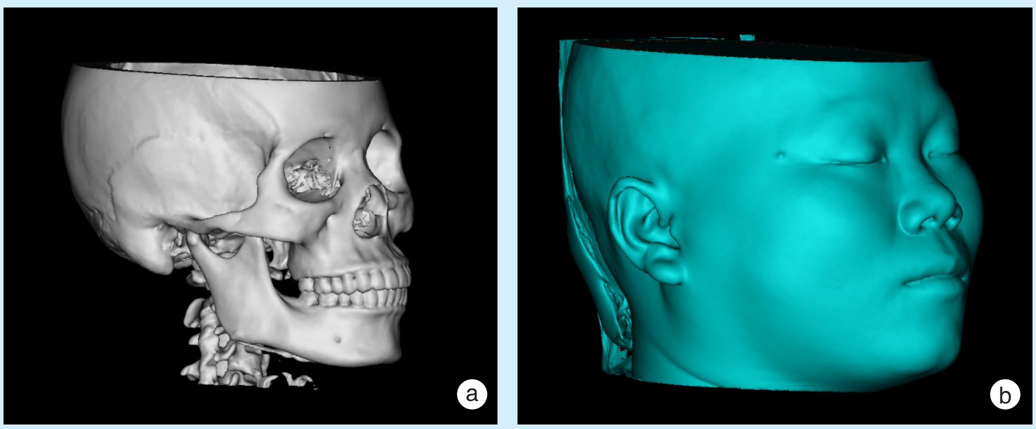
1.1　病例资料

本研究经南昌大学附属口腔医院医学伦理委员会批准（批号：2024055），纳入2025年6月—7月就诊的7例TMD患者，其中男性2例，女性5例；年龄（32.4±4.7）岁，所有患者签署知情同意书。

纳入标准：①符合TMD诊断标准的可复性/不可复性ADD或翼外肌功能紊乱；②需行翼外肌注射BTX-A治疗。排除标准：①凝血功能障碍（国际标准化比值>1.5）；②注射部位感染者；③具有BTX-A过敏史者；④妊娠/哺乳期及神经肌肉疾病患者。

1.2　影像采集与三维重建

采用螺旋CT（参数：120 kV，140 mAs，采集矩阵157×157，层厚0.6 mm）进行头颈部扫描，原始DICOM数据导入Mimics 21.0软件，通过阈值分割及区域生长算法完成颅面部三维重建（图1）。重建模型以STL格式导出，用于解剖定位及导板设计。



a：craniofacial bone structure；b：craniofacial skin structure

Figure 1　Spiral CT scan data were used to reconstruct craniofacial bone structure and skin in Mimics 21.0 software

图1　螺旋CT扫描数据在Mimics 21.0软件中重建颅面部骨性结构和皮肤

1.3　确定翼外肌上头和下头的骨性定位点

根据周围组织的关系和解剖定位，确定翼外肌上头和下头的骨性定位点（图2）。

翼外肌上头定位于颞下嵴中后2/3交界处下方（2.5±0.5）mm区域，该点对应翼外肌最厚肌腹横断面中心[15]。基于翼外板距皮肤表面的平均深度为（49.9±2.2）mm，翼外板平均宽度为（10.5±3.9）mm，上颌结节与翼外板之间的平均翼颌角为168.3°±15.8°[14]，先确定上颌结节最高点，翼外肌下头的骨性定位点位于上颌结节上15 mm，后5 mm的翼外板上[14]。

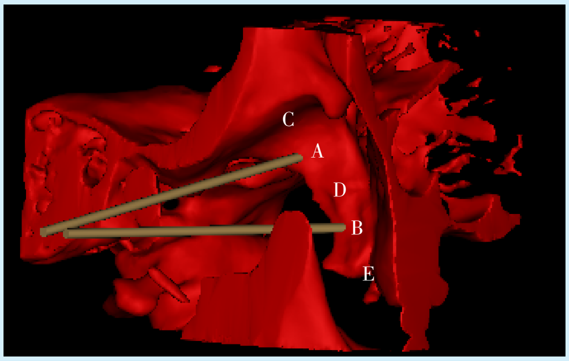
1.4　口外导板的设计和制作

导板设计分为导板注射路径确定、导板套管结构设计和导板固位稳定结构的设计（图3）。

导板注射路径设计：采用逆向工程原理，翼外肌上头路径以颧弓下缘为入路点，靶向翼外肌上头颞下嵴定位点，翼外肌下头路径自乙状切迹前缘入路指向翼外板定位点，双路径经调整规避骨性阻挡且互不干扰。

导板套管结构设计：设计2个套管数量（分别对应翼外肌上下头），套管参数内径2.0 mm，长度10.0 mm，套管长度和方向用于规范注射路径，指导翼外肌靶向注射。

导板固位稳定结构设计：导板稳定性是实现精准注射的前提。将导板延伸至外耳三角窝（深度3~5 mm），同时增加耳甲艇嵌合结构设计和耳甲舱负压吸附设计，覆盖范围为耳周围组织、下颌角和耳屏前组织。最后优化导板-骨面贴合度，使导



A: superior head of lateral pterygoid muscle; B: inferior head of lateral pterygoid muscle; C: infratemporal crest of sphenoid; D: lateral pterygoid plate; E: maxillary tuberosity

Figure 2　CT-guided localization of the attachment points for the superior and inferior heads of the lateral pterygoid muscle

图2　CT引导确定翼外肌上头和下头的定位点

板组织面与覆盖软组织紧密接触，增加导板的匹配度和稳定度。耳周适配系统通过负压吸附减少软组织位移，通过耳甲艇嵌合结构设计提升就位精度，依靠多点接触分散应力维持导板的稳定。导板整体厚度设计在2.5~3.0 mm（除了套管区域进行局部加厚，以确保靶向注射方向的准确性）以确保导板的强度，而不增加因自身重量因素影响固位稳定。

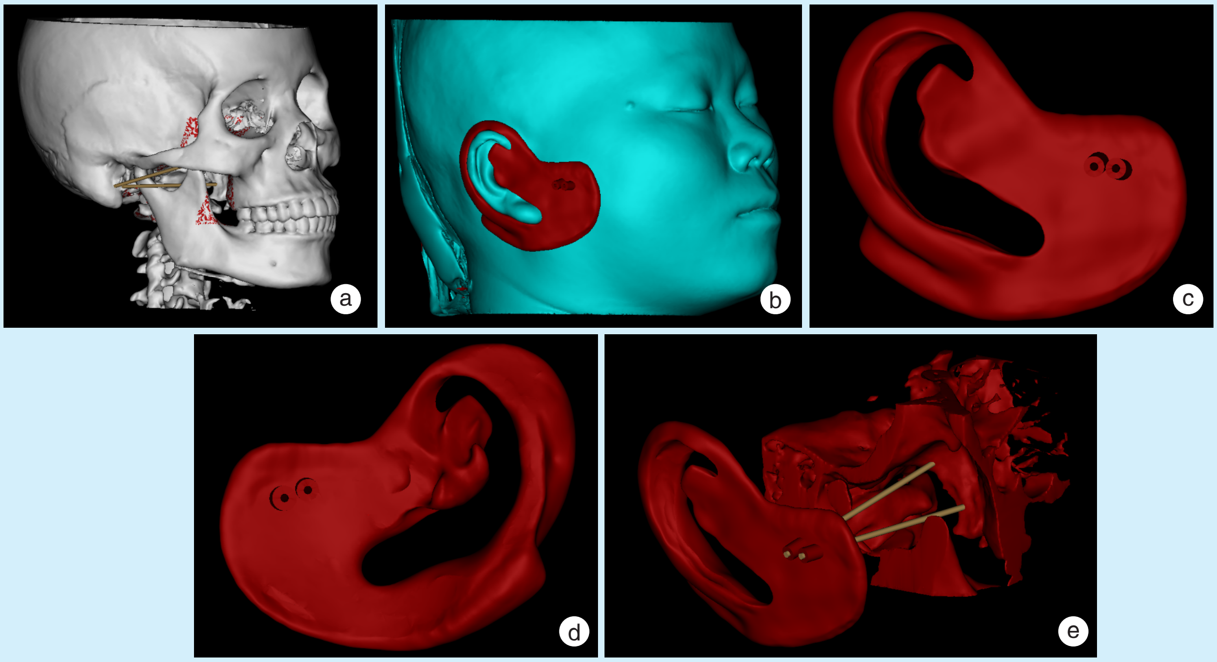
将设计完成的口外导板以“STL”格式导入“霖逸3D打印机”（DLP1080EA），使用GV - Model 2模型树脂（粤深械备20210822号）进行3D打印。打印好的导板使用95%酒精浸泡30 min消毒。

1.5　导板引导注射与精度验证

在翼外肌注射前，评估同一操作者多次放置导板的位置可重复性和不同操作者先后放置导板的位置可重复性。根据术前的CT数据进行导板设计和打印，并使用该口外导板进行翼外肌上头和下头靶向注射，术中注射完后留置注射针头即刻拍摄CT，将术前设计数据与术中注射完后CT数据导入VG Studio Max 3.0，执行软硬组织双模态拟合。基于颅面骨性标志点（如眶下孔、棘孔、颧弓下点，乳突最低点）的硬组织配准，用于计算预设路径与实际针轨的角度偏差及针尖距离误差。通过鼻根点、耳屏点及外眦点等面部软组织标志点配准，进行评估预设导板位置与实际注射时导板的位置差异。

1.6　临床效果观察方法及指标

所有患者完成单次注射治疗，7位患者共计注射治疗15个位点（翼外肌上头8个位点/翼外肌下



a：adjustment of the injection pathway and the needle exiting；b：stent positioned on the maxillofacial region；c：lateral view of the stent；d：medial view of the stent；e：extraoral stent for targeting the superior and inferior heads of the lateral pterygoid muscle

Figure 3　Design and manufacture of the CT guided navigation guide plate for targeting lateral pterygoid muscle

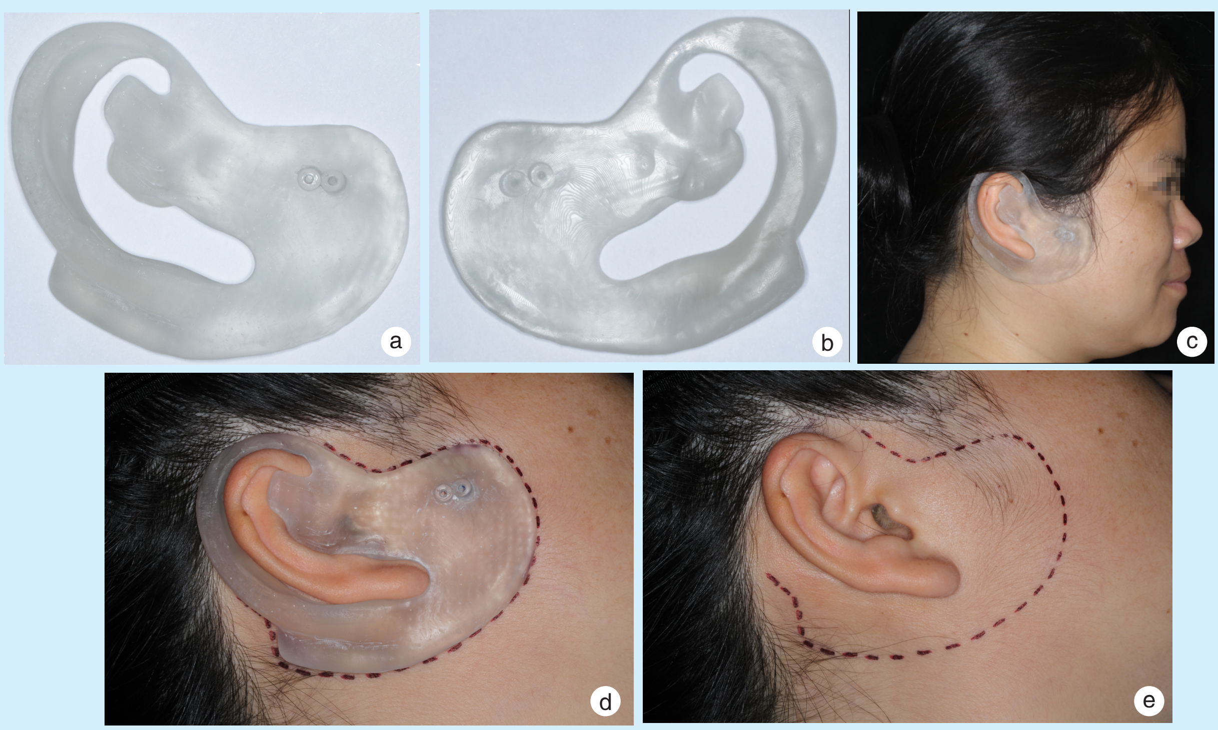
图3　CT引导下的靶向翼外肌导航导板的设计和制作

头7个位点；右侧9个位点/左侧6位点）；翼外肌注射药物为BTX-A（衡力，国药准字S10970037，兰州生物技术开发有限公司，中国）。临床效果观察方法及指标分别为：①采用视觉模拟评分（visual analogue scale，VAS）量化疼痛强度（0~10分，0为无痛，10为剧痛）。参考Rezazadeh等[16]研究中疼痛改善的程度，设定VAS≥3分作为疼痛改善的阈值，评估时间节点为基线、术后3 d、术后1、2、4周。②在术后2、4周，基于患者主观报告判定弹响是否改善。“弹响消失”或“弹响减轻至不影响生活”定义为改善。③在术后3 d、术后1、2、4周记录注射相关的出血、感觉异常、肿胀、感染、吞咽困难等并发症，一旦出现并发症密切关注，及时处理。

2　结　果

2.1　CT引导下靶向翼外肌导航导板具有良好的稳定性、固位力和可重复性

本研究通过医学图像处理程序技术，开发出一种创新性的口外导板系统，用于精准定位并靶向翼外肌上头和下头注射。这一技术方案类似于牙科种植手术中广泛应用的外科导板理念。采用高精度3D打印技术配合生物相容性树脂材料，确保导板的安全性和精确性，口外导板能顺利就位在患者颌面部（图4a～4c）。根据口外导板与外耳的形态贴合程度确定导板就位，在每次导板就位后用记号笔标记出导板的边缘，重复数次操作，通过观察边缘线的重叠性发现导板具有良好的位置重复性（图4d～4e）。导板位置可重复性从侧面证明了导板的固位和稳定性可靠，同时操作者在放置导板过程中也能感受到导板和固位力以及位置的唯一性，询问患者佩戴导板的移位情况和舒适度，患者表示导板戴入后异物感不明显，未发现脱落和移位的现象。



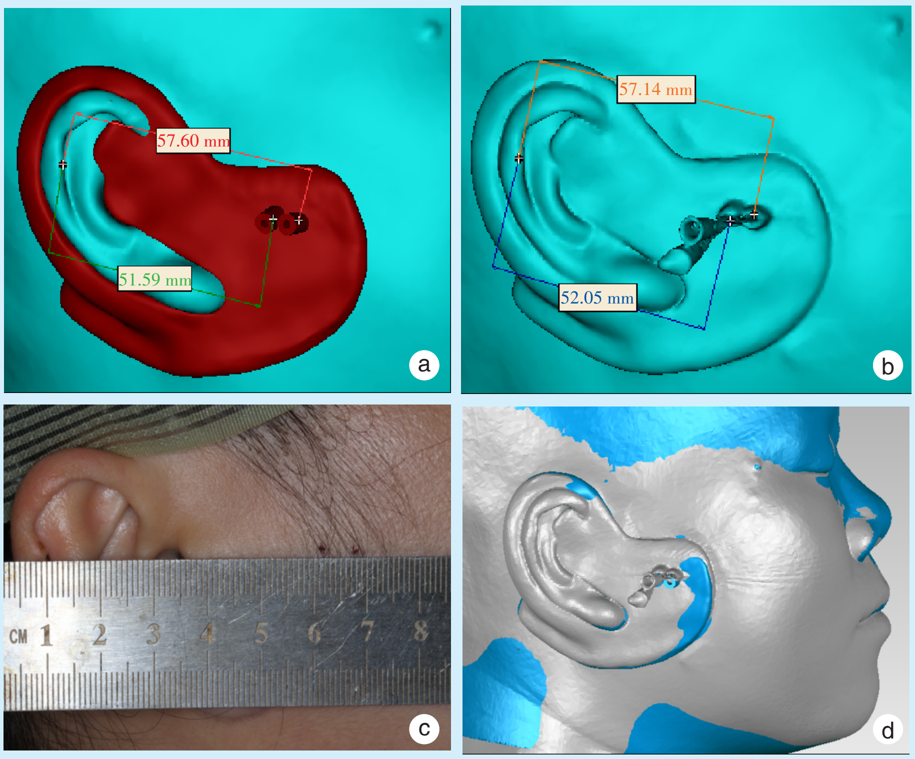
a-c: using high-precision 3D printing technology combined with biocompatible resin materials to ensure the safety and accuracy of the guide plate, the intraoral guide plate can be smoothly positioned in the patient's maxillofacial area. The outer side (a) and the inner side (b) of the 3D printed extraoral template and the template in position on the maxillofacial region (c). d & e: by observing the overlap of the edge lines, it was found that the guide plate has good positional repeatability. d: traced edge contour lines of the stent plate edge after repeated placement; e: edge contour lines of the stent plate edge after two repeated placements

Figure 4　The CT-guided navigation guide plate for targeting lateral pterygoid muscle target has good stability, retention force, and repeatability

图4　CT引导下靶向翼外肌导航导板具有良好的稳定性、固位力和可重复性

2.2　CT引导下靶向翼外肌导航导板的位置准确性

设计导板套管到耳轮结节的距离分别为57.60 mm和51.59 mm(图5a),实际注射导板到耳轮结节的距离分别为57.14 mm和52.05 mm(图5b),实际注射进针点到耳轮结节的距离分别为57.9 mm和51.8 mm(图5c),这说明导板具有良好的位置准确性。设计导板和实际注射导板的3D表面重叠发现两个导板具有良好的边界轮廓吻合性(图5d),但表面的拟合度有所降低,这可能是由于佩戴导板后软组织承受一定压力,软组织表面发生部分形变有关。



a: preset helix tubercle-to-tragus distance in stent design; b: achieved cannula-to-helix tubercle distance during actual injection. c: the distance from the injection entry point to the helix tubercle; d: 3D surface matching between designed and positioned stent

Figure 5　Positional accuracy of the CT guided navigation guide plate for targeting lateral pterygoid muscle

图5　CT引导下靶向翼外肌导航导板位置的准确性

2.3　CT引导下靶向翼外肌导航导板注射的精准性

基于颅骨标志的CT拟合显示,预设针轨与实际针管的重叠率达92.3%。可视化偏差分析证实针管偏离量集中于−2~1 mm区间。对7例患者15个注射位点定量评估显示,翼外肌上头注射针尖角度偏差2.49°±0.17°,针尖距离偏差(1.96±0.25) mm;翼外肌下头注射针尖角度偏差2.31°±0.16°,针尖距离偏差(1.65±0.21) mm。所有15次注射角度误差≤2.5°,距离误差≤2 mm,达到外科导航精度标准(<3 mm临床可接受阈值)。见图6。

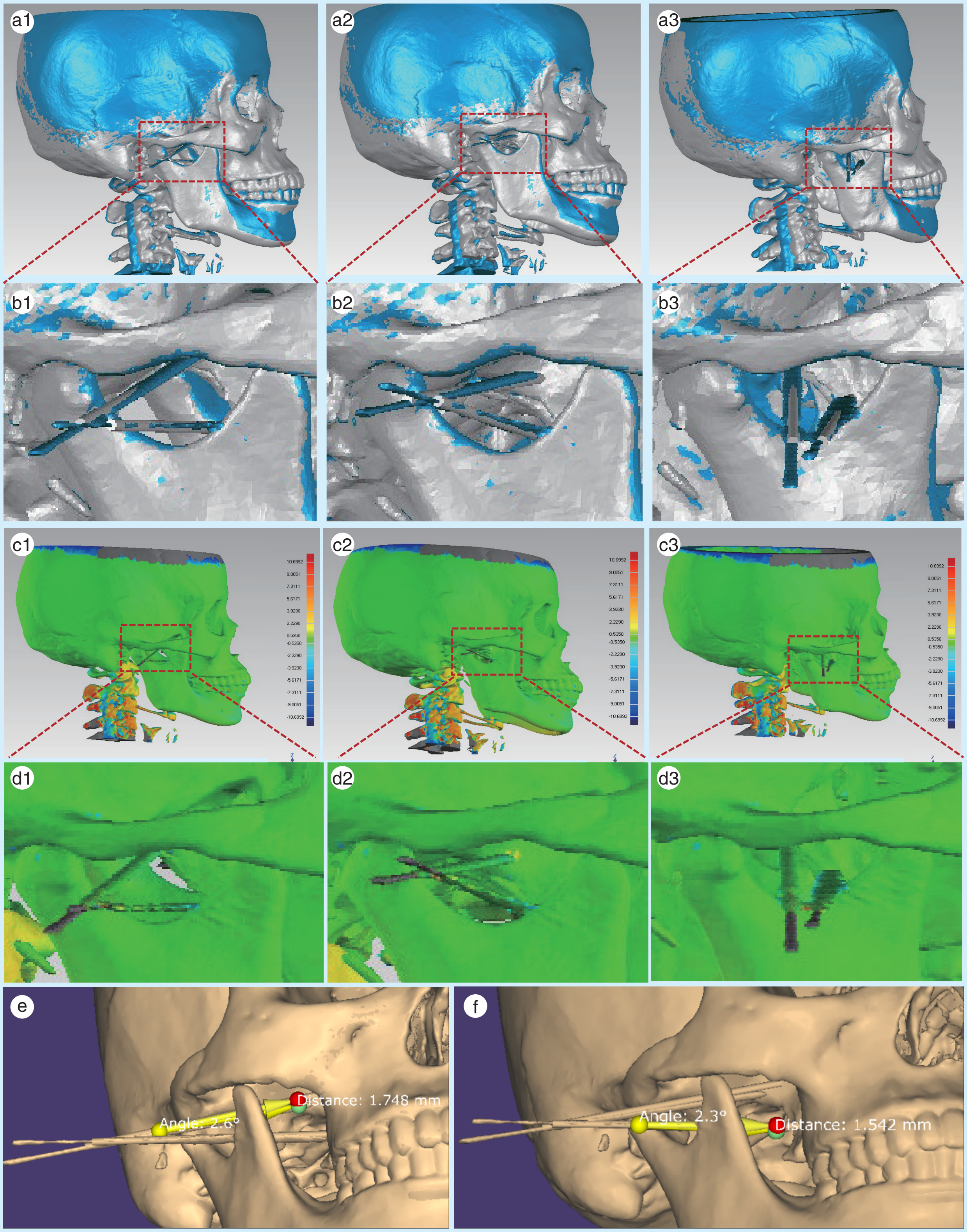
2.4　CT引导下靶向翼外肌导航导板引导注射的临床效果及并发症观察

术后3 d 60%患者(9/15)达到VAS显著改善(VAS值下降≥3分,VAS均值由6.5降至3.8),术后2周改善率提升至85%(13/15,VAS均值由6.5降至2.4),术后4周维持86.7%(13/15,VAS均值2.2)。弹响改善方面,72%患者(11/15)在术后2周报告弹响减轻或消失,该比例在术后4周时稳定在75%(11/15)。并发症监测发现2例轻微不良反应:1例(1/15,6.7%)出现单侧注射局部肿胀,经24 h冷敷后消退;1例(1/15,6.7%)出现短暂针刺感,48 h内自发缓解。未观察到感染、出血、神经损伤或其他严重不良事件。

3　讨　论

3.1　BTX-A靶向翼外肌精准注射的临床必要性

ADD和翼外肌疼痛作为TMD的核心亚型,治



a1-b3: CT bone registration pre- and post-injection. a1: lateral overview of registered pre- and post-injection CT volumes; a2: registered view targeting the superior head of LPM; a3: registered view targeting the inferior head of the LPM. b1-b3: magnified views of a1-a3, respectively. c1-d3: color-mapped 3D deviation analysis. c1: lateral overview of surface deviations; c2: targeting error in the superior LPM head; c3: targeting error in the inferior LPM head. d1-d3: magnified views of c1-c3, respectively. e: angular deviation and distance between the guide tube and injection needle for the superior LPM head. f: angular deviation and distance between the guide tube and injection needle for the inferior LPM head. LPM: lateral pterygoid muscle

Figure 6 Targeting accuracy of the CT guided navigation guide plate for targeting lateral pterygoid muscle

图6 CT引导下靶向翼外肌导航导板引导注射的准确性

疗手段有药物治疗、咬合板治疗、行为干预、关节腔注射甚至手术治疗，目前没有证据表明哪种治疗方案效果最佳[17-18]。BTX-A自1980年首次用于治疗斜视和眼睑痉挛[19]。目前，BTX-A的适应证广泛，包括治疗肌肉痉挛性疾病（如面肌痉挛、眼睑痉挛等）、缓解慢性偏头痛以及用于美容领域减轻皱纹等[20-21]。在口腔领域，BTX-A可用于治疗TMD和咬肌肥大等[22-23]，通过注射BTX-A可减轻咀嚼肌的过度活动，改善关节区和翼外肌区的疼痛以及关节弹响[24-25]。

然而，BTX-A注射的安全隐患不容忽视。文献已报道BTX-A注射可出现暂时性和持续性并发症（如常见的并发症眼部并发症、面部不对称与功能障碍），甚至是罕见的全身性并发症（吞咽困难、呼吸障碍及全身无力等）[26-27]。这些并发症部分需要观察对症处理，有些需要立即进行医疗干预。值得注意的是，最近研究关注到BTX-A重复注射可诱发下颌骨皮质厚度减少6%及髁突骨质减少[28-29]。这就要求药物必须精准作用于目标区域以规避剂量相关性骨代谢紊乱。传统盲法注射因翼外肌深居颞下窝、毗邻上颌动脉及翼静脉丛[30]，面临35%定位误差率和40%的神经血管损伤的双重风险[31]。定位误差和神经血管损伤风险的研究的操作者为外科医生，而对于经验缺乏的新手注射的风险可能更高。刘伯彦等[32]的研究发现数字化导板技术可以大幅度提高治疗的精准度，辅助口腔复杂的治疗操作。Custódio等[33]的尸体研究结果也证实导板引导的翼外肌注射角度和距离偏差小，针头脱位的概率极低，认为导板注射可能是一种可靠的注射工具。Yoshida等[34]在数字化导板引导下将BTX-A精准注射到TMD患者的翼外肌，发现数字化导板可将注射不当引起的并发症降到最低。翼外肌注射的疗效和安全性高度依赖于精准的靶向注射，本研究开发的基于三维解剖定位的导航技术，不仅是提升疗效的核心路径，更是规避医源性损伤的必然选择。

3.2 CT引导下靶向翼外肌导航导板系统与已有翼外肌注射技术的比较

咬肌和颞肌通过临床触诊就能准确定位，可通过直接触诊进行BTX-A注射[35]。而翼外肌注射BTX-A的报道相对较少，因为翼外肌位于面深部，临床触诊难以准确定位翼外肌，且触诊假阳性率高[36]，加上翼外肌盲法注射的低准确率和高神经血管风险，这就强调必须制定翼外肌安全注射治疗方案。目前研究者们已应用的翼外肌注射技术比较见表1。

肌电图引导作为目前临床应用最广泛的翼外肌定位技术[37]，肌电图能够提供肌肉电活动信息，大致定位翼外肌区域，却无法精确判断针尖是否到达目标肌肉内部，更难以区分翼外肌的上头和下头。这可能导致BTX-A误注入翼外肌下头，导致下颌侧向运动暂时受限和大张口时下颌偏斜等不良反应。此外，肌电图引导高度依赖操作者经验，需要由专业的神经科医生执行，且存在较高的假阳性率，这些因素限制了其在临床中的普及应用。超声引导作为一种实时成像技术，理论上可直观显示针头轨迹和肌肉结构[38-40]。然而，由于翼外肌位置深在，且周围有髁突、颧突和下颌切迹等骨性结构的阻挡，超声探查面临巨大挑战[41]。临床实践表明，超声引导要求医生必须熟悉颞下窝区域的超声解剖和熟悉超声成像的原理，这导致超声引导下翼外肌注射需要很长的学习曲线。此外，一般情况下，口腔诊疗常规中没有配备超声设备，这又额外增加了超声设备的购置和维护成本。MRI导航引导下的BTX-A注射是一种新型引导技术，该技术通过术前MRI获取翼外肌解剖数据，再借助专业规划软件确定靶区[42]。但导航系统价格昂贵，术前准备复杂，安装耗时较长，这些因素制约了其在临床的推广应用。从卫生资源配置角度看，导航引导技术可能不适合作为TMD的一线治疗方案，而应该是难治性病例的备选方案。还有研究者在关节镜引导下进行注射，关节镜下翼外肌注射技术的优势在于可以直接可视化关节结构[43]。通过关节囊小切口，术者不仅可进行BTX注射，还能同步进行翼外肌上头部分切除术[44]。然而，关节镜属于有创操作，且需要专门的手术设备和经验丰富的外科团队。因此关节镜技术的高成本和有限的可及性使其难以成为TMD常规治疗手段，仅适用于特定难治性病例。最后，通过牙齿固位的口内导板[45]引导的注射技术虽然操作相对简便，也更符合牙医口内操作习惯，但其准确性受多重因素制约。患者张口度直接影响操作空间，对于伴有严重疼痛和张口受限的患者，无法通过口内入路进行引导下翼外肌注射，而疼痛和张口受限是ADD患者最常见的症状；其解剖学研究显示，冠突与上颌骨之间的空间常常极为狭窄，而口腔粘膜穿刺位点很难标准化，导致注射深度变异大，极可能损伤神经血管结构，因此通过口内途径

表1　不同LPM注射引导技术的比较分析

Table 1　Comparison of different LPM injection guidance techniques

Technical Parameter	Be able to distinguish LPM superior / inferior bellies	Equipment cost	Technical dependence	Equipment dependence	Learning curve	Advantages	Disadvantages
Blind/landmark-guided	No	None	High	None	Variable (Short-Long)	No additional equipment required	Low accuracy, high risk of neurovascular injury
Electromyogram-guided	Partially	Moderate	High	High	Relatively long	Provides muscle electrical activity information	Cannot precisely determine if needle tip is within target muscle
Ultrasound-guided	Possible	Relatively high	High	High	Relatively long	Real-time imaging	Deep LPM location, complex surrounding hard/soft tissues, prone to obstruction
MRI-navigated	Yes	Very high	High	High	Long	High soft tissue imaging quality & resolution	Expensive system, complex preoperative preparation, time-consuming setup
Arthroscopically-guided	Excellent	Very high	High	High	Relatively long	Direct visualization of joint structures	Specialized equipment required
Intraoral guide	No	Low	Low	Low	Short	Relatively simple operation, aligns with dentists' intraoperative habits	Requires combination with ultrasound or electromyogram for improved accuracy; limited in patients with restricted mouth opening or narrow coronoid-maxilla space
Guide technique in this study	Yes	Low	Low	Low	Short	Simple operation, wide applicability, suitable for broad patient populations	Requires long-term clinical outcome observation

LPM: lateral pterygoid muscle

难以实现精准安全的药物注射[46]，通常需要结合肌电图或超声等辅助手段。

本研究开发的CT导航口外导板系统基于术前CT三维重建精准标定翼外肌上下头附着点(颞下嵴与翼外板)，结合逆向工程规划双独立注射路径，首次实现解剖分区的选择性靶向；其次，利用颧弓下缘与乙状切迹前缘形成的天然骨窗设计口外入路，彻底规避张口度和口内软硬结构的限制[47]。最后，通过耳甲艇嵌合结构与负压吸附系统确保导板固位稳定性。本系统首次实现了翼外肌上下头解剖靶向注射。

3.3　靶向翼外肌注射提高临床疗效

本研究通过分靶翼外肌注射BTX-A，在术后3 d即观察到60%患者疼痛程度显著改善(VAS下降≥3分)，较Rezazadeh等[16]研究中BTX-A组的1周疼痛缓解时间提前4 d。这一结果表明，解剖精准靶向注射能够使BTX-A集中作用于目标肌肉，从而实现单位剂量的疗效最大化，加速药物的肌松效应，从而更快速地缓解患者的疼痛症状。这种精准的药物分布不仅提高了治疗效果，还减少了不必要的药物使用量，降低了潜在的副作用风险[48]。术后4周，86.7%患者维持疼痛缓解，同时75%患者(11/15)报告弹响减轻或消失，这个结果与Blanco-Rueda等[25]和Sari等[49]的结果一致，短期疗效的稳定不仅是由于翼外肌的精准靶向注射，而且翼外肌分靶注射阻断了翼外肌痉挛-ADD的恶性循环，从源头改善关节盘的力学环境。值得注意的是，零神经血管损伤的记录证实了导板对

颞下窝高危区域的保护效能，为高精度注射的安全性设立新标准。这些结果发现不仅确立了导板技术作为翼外肌功能紊乱一线干预手段的临床地位，更揭示了翼外肌功能亚区（上头/下头）靶向治疗对未来个体化方案具有指导意义。

3.4　CT 引导下靶向翼外肌导航导板系统的临床应用前景与未来研究方向

本导板系统在 TMD 治疗领域展现具有较广的临床应用前景，在适应证方面，其可延伸至慢性关节脱位、肌张力障碍等翼外肌功能亢进性疾病；在技术整合层面，本导板预定位功能可以结合超声实时监控双模导航，可应对血管走行异常等术中变异；在卫生经济学视角，该技术设备依赖度低（仅需 CT+3D 打印），为基层医疗提供可行方案。然而，本导板系统也存在缺陷，首先，严重骨畸形（如Ⅱ类错颌）患者因解剖变异可能导致导板适配误差增大，需开发人工智能辅助的个性化设计算法；其次，术中肌肉收缩引起的动态靶点位移尚未量化，未来可融合表面肌电监测实现动态校准；最后，尽管导板降低技术门槛，但基层医生仍要熟悉注射部位的解剖结构。值得注意的是，本研究病例数有限，随访时间短，未来需要更多随机对照试验验证长期临床疗效和并发症。

本研究通过融合医学影像三维重建、计算机辅助设计与增材制造技术，成功开发一种基于 CT 导航的口外导板系统，首次实现翼外肌上头和下头的解剖分靶注射。该技术不仅为 TMD 提供首种可区分翼外肌功能亚区（上头牵拉关节盘/下头主导侧向运动）的靶向治疗方案，更建立了“解剖精准化—操作标准化—疗效可预测化”的治疗开辟了新途径。这一技术不仅具有临床实用价值，也为探索肌功能调控在关节盘复位中的作用机制提供了研究工具。

【Author contributions】 Huang M designed and executed the research, and wrote the original draft. Ouyang SB contributed to technical development and reviewed the manuscript. Yan QY was responsible for data visualization. Zeng YX conducted literature investigation. Liao L supervised the research and coordinated resources. All authors read and approved the final manuscript as submitted.

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