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自体血管化游离骨皮瓣及种植体在颌骨缺损中的应用研究进展

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摘　要

颌骨缺损常源于肿瘤、创伤或先天性发育畸形等疾病，严重影响患者的面容及咀嚼、吞咽、语言等生理功能。目前，自体血管化游离骨皮瓣移植仍是颌骨重建的“金标准”。随着数字化技术的应用与骨内种植体技术的深度融合发展，颌骨重建已进入功能与形态并重的精准修复阶段。本文就临床常用自体骨瓣的生物学特性、种植体恢复咬合功能的影响因素及数字化技术的辅助作用进行综述。

关键词

颌骨缺损，自体血管化骨皮瓣，骨移植，种植体，数字化技术

Advances in the Application of Autologous Vascularized Free Bone-Panniculus Flaps and Implants in Mandibular Defects

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Abstract

Mandibular defects often result from conditions such as tumors, trauma, or congenital developmental abnormalities, significantly impacting patients' facial appearance and physiological functions including chewing, swallowing, and speech. Presently, autologous vascularized free bone-skin flap transplantation remains the gold standard for maxillofacial reconstruction. Advancements in digital technology and its deep integration with intraosseous implant techniques have propelled maxillary reconstruction into a new era of precision restoration that prioritizes both function and form. This article reviews the biological characteristics of commonly used autogenous bone grafts in clinical practice, factors influencing the restoration of occlusal function by implants, and the auxiliary role of digital technology.

Keywords

Mandibular Defect, Autologous Vascularized Bone-Skin Flap, Bone Grafting, Dental Implant, Digital Technology

1. 引言

上下颌骨解剖结构精密且复杂，承载着咀嚼、言语、吞咽及呼吸等关键生理功能。颌骨缺损修复重建旨在恢复形态与功能，这一过程融合了口腔颌面外科、口腔修复科、口腔种植科等多个学科领域[1]，自 1989 年首次报道应用游离组织瓣结合骨内种植体修复下颌骨缺损以来，显微血管外科与骨种植技术的协同演进推动了该领域的显著发展[2]，目前，自体血管化游离骨皮瓣移植仍是颌骨重建的“金标准”[3]。本文拟就临床常用移植骨的种类及其生物学特性进行系统阐述，并深入探讨影响种植修复效果的关键因素，以便为临床医师在供区选择及修复策略制定方面提供有益参考。

2. 自体血管化游离骨(皮)瓣类型

血管化自体游离骨移植，通过切取患者特定部位的自体游离骨及其配套营养血管，制备成带血管蒂的骨(皮)瓣，随后通过微血管吻合技术建立起与受区血管的循环联系。该技术的核心优势在于移植骨瓣可即刻获得充足的动脉灌注与静脉回流，从而保障其在缺损部位的长期存活。得益于丰富且持续的血供，该类骨瓣展现出卓越的抗感染能力，不仅利于实现早期的骨原位愈合，且远期骨吸收率较低。临床上，腓骨、髂骨、肩胛骨、桡骨、肋骨、股骨及跖骨等均可作为重建颌骨的备选供区，其中以腓骨、髂骨和肩胛骨的应用最为广泛[4]。

2.1. 腓骨瓣(Fibular Flap)

作为近年来下颌骨缺损重建中最常用的自体骨来源，其主要优势在于：形态规则且易于截骨塑形；血流灌注良好，成骨效率高；可提供 20 cm 以上的超长骨段；血管管径适中且制备简便，尤其支持受区与供区两组团队同步作业，显著缩短手术时间。然而，腓骨瓣也存在一定局限性，如垂直高度不足、皮瓣灵活性较差、供区植皮坏死率偏高、术后肢体固定时间较长及潜在的血管损伤风险[5] [6]。其核心缺陷

在于缺乏足够的垂直高度：腓骨平均厚度仅为 12~15 mm，与成年人下颌骨高度差距较大，仅接近萎缩性无牙颌患者的水平[7]。目前，临床上常采用垂直牵张成骨、双管折叠技术[6] [8]、或将腓骨置于牙槽嵴高度并配合下缘重建板加自体骨移植等策略来补偿高度不足[9] [10]。但需注意的是，腓骨垂直牵张的可预测性较差，牵张不当可能导致骨段舌侧倾斜、基底骨折及边缘骨吸收，进一步导致种植失败[11]。同时，在双管腓骨内行种植体即刻精准植入也极具挑战性[12]，在临床应用中需慎重评估。

2.2. 髂骨瓣(Iliac Flap)

髂骨瓣凭借其独特的生物学特性，在颌骨功能性重建中扮演着不可或缺的角色。其核心优势在于充足的骨量与天然的弧形轮廓，不仅有利于重塑面部形态，同时可提供 2~5 cm 的骨高度，可完美匹配上下颌骨重建的解剖需求。在下颌骨缺损重建时，可有效弥补腓骨瓣高度不足的问题[13]；上颌骨修复重建时，其骨高度可在重建牙槽骨缺损的同时重建眶下缘及鼻旁支柱、颧牙槽嵴支柱和翼上颌支柱，为后续种植修复提供空间[14]。此外，其丰富的松质骨含量与充足的血供，使其在处理术后放疗及放射性骨坏死导致的骨缺损时更具一定的生物学优势[15]。同时相较于腓骨瓣对截骨面密贴性存在依赖性，髂骨瓣具备更强的愈合潜能，无需截骨面之间的密切接触，部分病例仅需线性截断，骨段之间的 V 型缺损会在短期内迅速愈合但种植体的稳定性较腓骨低[16]。髂骨瓣局限性在于有效骨长度通常限于 9~10 cm 以内，且存在血供相对单一、肌皮瓣过于厚实及供区臃肿等不足，故大跨度骨缺损仍首选腓骨瓣[17]。

2.3. 肩胛骨瓣(Scapular Flap)

肩胛骨瓣作为一种由旋肩胛动脉供血的扁骨供区，其核心优势在于拥有较长的血管蒂以及自由度较高的大面积软组织皮岛，能有效满足颌骨缺损合并大面积舌、面、颈部组织缺损的复杂修复需求[18]，研究发现，肩胛骨骨皮质厚度随年龄增长而增加，且供区发病率较低，使其成为老年患者的理想选择；相比髂骨瓣，其肌皮瓣更显轻便且不显臃肿[5]。其主要局限性在于不能无法同时进行颌骨病灶切除及肩胛骨皮瓣制备双组团队同步作业。此外，由于缺乏足够的根尖骨宽度，大量患者无法进行后期种植体修复[19]。

在血管化骨瓣的综合评价中，腓骨瓣与髂骨瓣在骨体积及生物稳定性上表现更佳，均能容纳标准尺寸种植体，且术后边缘骨吸收率相似且均处于极低水平(<1 mm) [20] [21]。两者的并发症特征迥异，接受腓骨瓣重建的患者存在步态和四肢神经感觉异常，而髂骨瓣并发症血肿和疝局限于供体部位[22]。在功能恢复维度，腓骨瓣重建患者术后吞咽功能优于髂骨瓣，这可能归因于髂骨肌皮瓣过于臃肿，往往需要通过大量减容手术维持口腔卫生与种植体周围组织健康[23]。在临床诊疗上，髂骨瓣是下颌角伴软组织缺损的有牙颌患者的首选；而腓骨瓣则优先用于无牙颌、长距离缺损 (如下颌次全或全切除)及髁突重建[24] [25]。总体而言，两者在供区发病率、疼痛评分、言语、美学及长期生活质量评估方面具有相似性[22] [26] [27]。

3. 骨内种植体的应用

自 Brånemark 等学者率先将种植技术引入下颌骨功能重建领域以来，这一突破性尝试为颌骨缺损的功能性修复开辟了全新路径。目前，血管化骨移植联合种植体已成为临床实践中重建咬合功能的首选方案[28] [29]。在修复方式上，自体血管化移植骨种植修复可分为种植支持式固定义齿与种植支持式覆盖义齿两大类[30]。前者对重建骨段的解剖位点要求极高，理想的颌间距离需维持在 12~15 mm；若种植体长轴未能精准穿过前牙舌隆突或后牙牙合面，则需适当增加颌间距离以预留修复空间。相比之下，种植支持式覆盖义齿对骨段空间位置的容错率较高[31] [32]。此外，数字化辅助设计与制造(CAD/CAM)在恢复形态美学与咬合功能方面展现出显著优势。研究表明，数字化技术不仅能显著提升重建精度、缩短手术

耗时，还有助于优化重建质量并改善医患沟通。通过术前可视化数字排牙，医师可预先确定义齿形态并反向推求种植体理想位点，以此作为骨重建的参考航标，并借助手术导航或 3D 打印导板将设计精准转化为手术现实[30] [33]。

3.1. 种植体植入时机

目前，颌骨重建联合种植牙的时机主要分为以下三种策略：1) 预制骨瓣技术(Prefabricated Flaps)：即在骨瓣移植前 3 个月于供区预先植入种植体，待骨结合完成后，再行血管化骨瓣游离移植。该法允许在骨重建同期完成义齿修复，阿尔伯塔大学(UAH)等机构曾利用预制腓骨瓣进行尝试[34]，但受限于治疗周期，目前临床应用较少；2) 延期种植(二期植入)：这是目前最成熟且广泛应用的方法。其优势在于单次手术时间短，且有一段临床观察期以排除肿瘤复发；此时移植骨已与受区愈合，骨块稳定性更佳，利于数字化导板的精准引导；3) 同期种植(一期植入)：在颌骨重建过程中同步植入种植体。该法对手术精度要求极高，且术后调整空间有限[35] [36]。研究表明，同期与二期种植在存活率及安全性方面无显著差异[37]。同期种植体植入是安全的，一般不会对移植骨瓣的血管造成损伤，并且种植体存活率和修复成功率较高，数据显示其中上颌种植体存留率为 97.5%，下颌骨种植体存留率为 97.1% [38]。其优势在于手术入路开阔、减少手术频次并能早期恢复形态与功能。对于需接受术后放疗的患者，同期种植可在放疗开始前完成骨结合，从而降低种植体失败及放射性骨坏死的风险[39]，具有显著的成本效益。然而，该方法也存在一些弊端，如种植位点定位困难、种植体对放射治疗的潜在干扰，甚至可能发生种植体植入部位的肿瘤复发[40]，因此，对存在较高复发风险的恶性肿瘤切除病例，禁止采用种植体同期植入[12]。随着数字化技术的革新，基于虚拟手术设计(VSP)与 CAD/CAM 技术的“Jaw-in-a-Day”技术[36] [41]应运而生，实现了肿瘤切除、骨瓣移植、种植体植入及临时即刻修复的同日完成。这一技术充分体现了“以修复为导向”的重建理念，具有重要的临床推广价值。Levine 等[42]曾报道 1 例在颌面缺损重建同期完成腓骨瓣移植、骨内种植体植入及修复体即刻就位的病例。该方案虽能显著提前颌面外形与功能的恢复周期，但面临软组织重建难度高、单次手术耗时长等挑战。目前，此类同期修复重建的病例报告仍较为有限，尚缺乏大规模的长期成功率随访数据。

相比之下，二期种植通常在骨瓣移植愈合 6 至 12 个月后进行。若术中发现内固定钛板干扰种植位点，则需在二期手术中予以拆除。二期种植的优势显而易见：初次手术负担轻、骨段愈合稳定性高、利于制定更理想的种植修复计划，并能通过定期复查有效排除肿瘤局部复发的风险[43]。但手术次数及费用增加，恢复口颌功能延迟是二期植入种植体的显著缺点，患者往往需经历 12 个月以上的漫长周期方能完成最终修复[44] [35]。此外，患者在经历大型重建手术后产生的术后畏难情绪与手术恐惧，亦是影响其最终选择或完成种植修复的重要心理因素。

3.2. 种植体类型

研究表明，种植体品牌并非影响其存活率的关键因素[45]。目前市面上主流的种植系统(如 Biomet 3i、Nobel Biocare、Astra Tech、Straumann 及 Ankylos 等)均能有效应用于颌骨缺损的修复重建[46]。在表面特性方面，相较于传统的机加工表面(Machined)种植体，经表面改性处理的种植体失败率更低。这主要归因于粗糙表面增大了骨接触面积，从而显著加速了骨整合进程。此外，种植体长度与受区环境的交互作用亦不容忽视：与标准尺寸的种植体(长度为 10 mm 或更大)相比，短种植体放置在放射辐射场中时故障率更高[47]。

3.3. 种植体周围软组织处理

在颌骨缺损重建中，移植骨表面常覆盖含有丰富皮下脂肪及肌肉成分的复合皮瓣。这种松软肥厚的

软组织环境不利于种植体的长期稳定，极易诱发慢性炎症、肉芽组织增生，并最终导致种植体周围炎[48]。研究证实，种植体周围充足的角化黏膜对维持种植环境的生物学稳定性具有重要保护作用[49]。针对颌骨缺损患者普遍存在的角化黏膜缺失问题，临床中首选方案是在种植二期手术时行前庭沟成形术联合腭部角化黏膜移植。然而，对于大面积角化黏膜缺失或上颌肿瘤术后腭部供区受损的患者，自体黏膜来源常严重受限。在此情况下，游离薄层皮片移植成为理想的替代选择：利用取皮刀获取大面积皮片并将其固定于重建颌骨骨膜表面，可获得变薄且稳固的软组织，临床效果良好[50]。此外，组织工程化角化膜的问世[51]，为解决自体供区匮乏及避免二次供区损伤提供了极具前景的新思路。

3.4. 放疗对种植体的影响及相关并发症的预防策略

头颈部恶性肿瘤患者术后常需接受放疗，而放疗诱发的骨移植物坏死是导致种植修复失败的核心因素。电离辐射会直接损伤移植骨内的血管系统，导致微循环持续缺氧，并降低成骨细胞的活性与数量，进而削弱种植体的骨结合效能[52]。

3.4.1. 种植体植入时机的选择

目前，关于放疗区域血管化骨瓣内种植体骨整合的成功率报道不一，但临床对植入时机已达成基本共识。尽管有研究认为放疗后的植入时间并非影响总存活率的决定性因素[45]，但多数学者建议在放疗结束后至少等待 6 至 12 个月[47] [53]，以确保骨瓣血供恢复并提高植入的稳定性。研究进一步证实，放疗环境下上颌种植体的存活率低于下颌，且腓骨瓣内的种植体存活率低于天然颌骨[54]。此外，在既往受照区或发生过放射性骨坏死(ORN)的骨组织中，种植体丧失的风险显著升高[39]。

受照骨瓣与非受照骨瓣相比，其种植体丢失率约为后者的两倍，且失败高发期集中在植入后的前 6 至 12 个月[39]。尽管文献指出种植体存活率受植入时机、放疗模式、放射剂量(>50 Gy)及性别等因素影响[39] [45] [55]，但 ZenFilho 等[53]在 2016 年的系统评价中提出，放射剂量与植入时间并非种植失败的显著风险因素。因此，放疗对骨瓣移植种植预后的确切影响仍需深入研究。

3.4.2. 放射性骨坏死(ORN)的预防与处理策略

放射性骨坏死是头颈部放疗后最严重的并发症之一，其本质是一种无菌性缺血性骨坏死，而非感染性过程。在种植修复背景下，ORN 的发生不仅威胁种植体存活，还可能导致重建骨段的不可逆性损伤[56]。因此，术前评估与术中预防至关重要。

放疗前的全面口腔评估与处理是预防放射性骨坏死及相关并发症的基石。所有拟接受头颈部放疗的患者，均应在治疗前接受口腔颌面外科或牙科专科医师的全面口腔评估。对于无法保留的患牙应予拔除，活动性感染需及时治疗，并确保在放疗开始前预留充足的软硬组织愈合时间，通常建议至少为 10~14 天[57]。一项基于大样本人群的研究指出，放疗前 2 周内进行牙周洁治可使 ORN 的发生风险显著增加 1.28 倍；而在放疗前 6 个月内未接受洁治的患者，其 ORN 风险相对较低[57]。这一发现提示，有创性牙科预防操作应与放疗起始时间保持足够的时间间隔，以降低组织愈合不良及骨坏死的发生风险。

放疗期间及放疗结束后的持续性口腔维护对于降低远期并发症风险至关重要，具体措施包括以下几个方面：

氟化物的规范应用：常规使用 1.1%氟化钠凝胶进行局部涂氟，是预防放射性龋齿的有效手段，能够显著增强牙釉质的抗酸能力。现有研究证实，规范使用氟化物并不会显著增加放射性骨坏死的发生风险[57]。

氯己定漱口水的审慎使用：值得注意的是，氯己定漱口水的应用需格外谨慎。上述同一项大样本研究发现，氯己定的使用与 ORN 风险显著升高相关(风险比 HR 介于 1.83 至 2.66 之间)，可使口腔癌患者

的 ORN 风险增加 2.43 倍[57]。因此，氯己定应仅在有明确临床指征(如急性感染或术后短期控制菌斑)时短期使用，而不宜作为常规预防性漱口制剂。

终身定期随访：放疗后患者应建立终身牙科随访制度，建议每 3 至 6 个月进行一次口腔检查，以便早期发现并处理龋齿、牙周病等常见并发症，避免其进展至需要复杂手术干预的阶段。

高压氧治疗(HBO)的争议与进展：长期以来，高压氧治疗(HBO)被许多中心作为预防放疗后高危颌骨手术所诱发 ORN 的常规辅助手段。其理论基础在于通过提高组织氧分压，改善受照区域的氧合状态，从而促进血管新生与组织愈合。然而，近年来的系统评价与回顾性研究对其临床获益提出质疑。最新观点表明：现有证据尚不足以支持 HBO 作为常规预防手段[58]；对于无 ORN 病史的放疗患者，HBO 未能显著提高种植体存活率，但对于高风险患者(如放疗剂量 ＞60 Gy、骨瓣血供受损、既往 ORN 史)，HBO 仍可作为个体化辅助治疗选项[59]；国际口腔肿瘤学会等多学科组织发布的指南指出，在 ORN 的预防和管理中使用 HBO 很大程度上缺乏依据，支持其应用的证据有限，不应将高压氧治疗(HBO)作为预防颌骨放射性骨坏死的常规或标准措施，其角色应严格限于临床试验或经过多学科团队充分评估的、极为特殊的超高危个案[60]。

关注针对纤维化过程的药物组合 (如己酮可可碱、生育酚，有时联合氯膦酸盐，即 PENTOCLO 方案)为代表的靶向药物在治疗早期 ORN 方面显示出前景[61] [62]，这些可能在未来改变 ORN 的预防和管理格局。

3.5. 种植体植入并发症

在骨瓣重建区，种植体周围炎是最常见的并发症。其核心机制在于移植骨瓣携带的皮肤组织无法与种植体形成牢固的生物学封闭，导致种植体周围极易形成深盲袋，进而诱发细菌的侵袭与繁殖。研究表明，充足的附着龈在增强牙周组织抗机械刺激能力、减少菌斑滞留以及缓冲黏膜肌纤维生物张力方面具有不可替代的作用，是维护种植体周组织健康与美观的关键[63] 。但需警惕的是原发病灶处的肿瘤复发常与一期(同期)植入的种植体密切相关。其诱因可能包括：种植床在手术过程中的肿瘤细胞播种、金属种植体对局部放射剂量的背散射干扰，以及因吸烟、饮酒和慢性种植体周围炎导致的黏膜长期炎性刺激。因此，对于顽固、易复发的慢性种植体周围炎，临床中应进行严密监测和规范治疗，必要时须通过组织活检以排除复发或癌变可能[64]。

4. 数字化技术在自体骨瓣移植联合种植体植入的应用

数字化技术，特别是以咬合为导向(Occlusion-driven)的理念提出及应用，正在彻底改变自体骨瓣移植联合种植体植入的治疗范式。依托虚拟手术设计(VSP)、计算机辅助设计与制造(CAD/CAM)、3D 打印及手术导航等技术，实现了从最终义齿形态反推骨瓣截骨与种植体植入位置的确定，显著提升了颌骨修复重建的可预测性与功能美学效果[65]-[67]。

4.1. 以咬合为导向的反向设计工作流程

在自体血管化骨瓣联合种植体修复的数字化流程中，设计起点不再是骨瓣本身，而是最终的义齿形态与咬合关系。其工作流程如下：

数据采集与虚拟排牙：通过口腔锥形束 CT (CBCT)获取患者颌骨及供区(如腓骨、髂骨)数据，结合口内扫描或石膏模型扫描数据，构建数字化牙列模型。在虚拟环境中进行排牙，确定理想的牙弓形态、咬合平面及颌间距离[66] [68]。

反向设计种植体位点：以最终义齿咬合为导向，确定种植体的理想三维位置(包括轴向、深度、角度)，

并确保其位于骨量充足区域。此步骤需同时考虑修复体固位方式(螺丝固位或粘接固位)、美观区穿龈形态及清洁可维护性[65] [69]。

骨瓣截骨与塑形设计：将种植体理想位置反推至供区游离骨模型中，确定骨段截取长度、角度及排列方式(如腓骨的双管折叠或单段放置)。通过 VSP 软件模拟骨段拼合，确保种植体在重建后位于牙槽嵴顶理想位置，同时避免与内固定螺钉、重建板发生空间冲突[58]。

导板设计与制造：基于上述设计，分别生成供区截骨导板、受区定位导板及种植导板，并通过 3D 打印技术制造。导板可实现术中精确截骨、骨段定位与种植体植入，减少术中误差[68] [70]。

临时修复体的预制：在设计种植体位点的同时，可同步设计并打印临时固定修复体，实现“Jaw-in-a-Day”理念下的即刻功能恢复[66] [68]。

4.2. 骨量受限条件下数字化平衡策略

尽管数字化设计可大幅提升手术精度，但在骨量受限(如腓骨垂直高度不足、肩胛骨宽度有限等)情况下，解剖重建与功能重建之间的矛盾仍需协调。数字化技术在此类复杂情境中提供了多种优化路径：

骨段空间重构：在腓骨瓣中，若垂直高度不足，可通过双管折叠技术将骨段上下叠放，以增加牙槽嵴高度。数字化技术可精确模拟折叠后骨段的相对位置、血供路径及种植体植入空间，避免压迫血管蒂或影响骨愈合[71] [72]。

种植体位点优化：在骨宽度不足(如肩胛骨)或存在骨外突起形畸形时，VSP 可辅助选择种植体植入的“最佳妥协位点”，如偏离理想牙位但仍在可修复范围内[73]，或选择倾斜植入以避开骨缺损区域[74]。

修复体补偿设计：当骨量不足以支持所有种植体理想植入时，可通过修复体设计(如义齿翼延伸、覆盖义齿、角度基台等)进行功能补偿[75]。此外，数字化虚拟排牙可在术前模拟修复体形态，评估其美观与咬合可行性。

虚拟血供评估：在高风险区域(如双管腓骨或髂骨瓣)，数字化技术还可模拟血管走行，评估种植体植入对血供的潜在影响，避免术中意外损伤[76]。

多方案模拟与风险预判：依托 VSP 软件，可在术前生成多种重建方案(如不同供骨来源、不同种植体数量与分布)，并量化评估各方案在骨量、咬合、美学等方面的优劣，辅助术者与患者共同决策。

5. 总结

自体血管化游离骨瓣移植联合种植修复已广泛应用于颌骨缺损的临床实践，但实现形态与功能的完美重建仍面临诸多技术挑战。当前，“以咬合为导向”的修复理念已成为主流。依托数字化技术的飞速发展，手术的可预测性与精确度显著提升，自体骨移植同期种植修复在恢复颌骨外形及咬合功能方面展现出巨大的临床价值及应用前景。尽管目前相关病例报告较少，且长期成功率的循证医学证据尚不充分，但随着数字化技术的不断革新与多学科的深度融合，颌骨缺损重建技术将日趋完善，从而显著改善患者的生活质量。

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