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·专家论坛·

舌癌术后半舌缺损修复重建技术及研究进展

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【摘要】 舌癌术后半舌缺损的修复重建是头颈肿瘤外科中最具挑战性的任务之一，其核心目标是在肿瘤学安全基础上兼顾形态恢复与功能重建。近年来，随着显微外科及功能导向性重建理念的发展，舌癌术后半舌缺损修复重建已由传统直接缝合和带蒂皮瓣逐渐发展为以游离皮瓣为主，并进一步向精准化、功能化方向演进。部分皮瓣改良设计，通过优化舌体三维形态与舌-腭接触关系，在吞咽功能改善方面显示出新优势。与此同时，感觉神经修复、动力性重建、多维感觉恢复及数字化/人工智能辅助设计等新策略，正推动舌癌术后半舌缺损修复重建由“形态替代”向“功能重建”进一步转变。然而，目前该领域仍存在高等级循证证据不足、功能结局评价标准不统一、不同修复策略间缺乏高质量比较研究等问题。总体而言，当前研究提示术后功能恢复不仅与手术切除范围、残舌保留程度等基础条件相关，更与皮瓣类型、感觉神经修复、动力性重建及放疗等因素密切相关。未来仍需建立统一的功能评价体系，并开展多中心、前瞻性长期随访研究，以进一步明确不同修复策略的最佳适应证及真实临床获益，推动多维感觉恢复、动力性重建、人工智能辅助设计等技术进步、落地，使舌癌术后半舌缺损修复重建向更精准化、个体化及功能导向性方向发展。

【关键词】 舌癌；　手术切除；　半舌缺损；　修复重建技术；　术后功能评估；　吞咽；　语音；　数字化设计；　人工智能辅助重建
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Reconstructive techniques and research advances for hemiglossal defects following tongue cancer surgery

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【Abstract】 Reconstruction of hemiglossal defects following tongue cancer surgery remains one of the most challenging tasks in head and neck oncologic surgery, with its core objective being the restoration of morphology and function while ensuring oncological safety. In recent years, with advances in microsurgery and the concept of function-oriented reconstruction, hemiglossal defect construction following tongue cancer surgery has gradually evolved from traditional primary closure and pedicled flaps to predominantly free flaps, further progressing toward precision and functionalization. Certain modified flap designs, by optimizing the three-dimensional tongue contour and tongue-palate contact relationship, have demonstrated new advantages in improving swallowing function. Meanwhile, emerging strategies, including sensory nerve repair, dynamic reconstruction, multidimensional sensory recovery, and digital/artificial intelligence-assisted design, are driving the shift of hemiglossal defect reconstruction following tongue cancer surgery from “morphological substitution” toward “functional restoration.” However, challenges persist in this field, including insufficient

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high-level evidence, lack of unified functional outcome evaluation criteria, and a dearth of high-quality comparative studies among different reconstructive strategies. Overall, current evidence suggests that functional recovery of the tongue after hemiglossal defect reconstruction is not only related to fundamental factors, such as the extent of surgical resection and the degree of residual tongue preservation, but it is also closely associated with flap type, sensory nerve repair, dynamic construction, and radiotherapy. Future efforts should focus on establishing a unified functional evaluation system and conducting multicenter, prospective, long-term follow-up studies to further clarify the optimal indications and genuine clinical benefits of different reconstructive strategies. This would assist in the promotion of the translation and advancement of technologies, such as multidimensional sensory recovery, dynamic reconstruction, and artificial intelligence-assisted design, and steer hemiglossal defect reconstruction following tongue cancer surgery toward greater precision, individualization, and function-oriented development.

【Key words】 tongue cancer; surgical resection; hemiglossal defects; reconstructive techniques; postoperative functional assessment; swallowing; speech; digital design; artificial intelligence-assisted reconstruction
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舌缺损可由肿瘤切除、外伤、感染及先天畸形等多种原因引起，其中舌癌根治性切除是获得性舌缺损最常见的原因之一[1]。近年来，随着间室手术[2]、浸润深度[3]（depth of invasion，DOI）等理念的提出和应用[4]，舌癌外科治疗逐渐由单纯扩大切除向精准化、个体化切除转变。与此同时，随着患者长期生存率提高，术后吞咽、语音及生活质量等功能性指标日益成为评价治疗效果的重要结局指标，舌缺损重建的目标也逐渐由单纯创面修复转向兼顾形态恢复与功能重建。半舌缺损（hemiglossal defect）是舌癌术后具有代表性的舌缺损类型。目前，半舌缺损的修复重建方式已由直接缝合、带蒂皮瓣逐步发展至以游离皮瓣为主的重建模式，并进一步向功能导向和精准化方向发展。除传统皮瓣重建外，皮瓣形态改良、神经功能修复、动力性重建以及数字化和人工智能辅助设计等新策略不断涌现[5-6]，为改善术后功能提供了新的思路。然而，现有研究仍存在缺损分类标准不统一、功能评价体系差异较大、高质量比较研究不足及长期随访资料有限等问题，不同修复策略的真实临床获益及最佳适应证尚缺乏充分证据支持。基于此，本文聚焦舌癌术后半舌缺损，阐述主要修复重建策略、常用皮瓣及改良型皮瓣设计的发展现状，总结功能性重建的新进展，吞咽、语音和生活质量等功能结局的影响因素和评估方法[7]，以期为舌癌术后半舌缺损的个体化和功能导向性修复重建提供参考。

1　舌癌术后半舌缺损修复重建

1.1　舌癌术后半舌缺损修复重建的挑战与目标

舌癌术后半舌缺损修复重建的核心目标在于兼顾创面封闭、形态恢复与功能重建。与其他口腔软组织不同，舌在吞咽、食团推进及发音过程中承担高度复杂的动态功能，因此，成功的舌修复重建不仅需要填补缺损[8]，更需要恢复足够的体积、适宜的空间构型以及与残余舌协同运动的潜力[5]。

对于半舌缺损而言，其修复重建难点在于缺损通常累及一侧舌肌、黏膜及部分神经血管结构，导致舌体对称性、肌肉连续性和运动协调性明显破坏。术后重建组织能否帮助残舌形成有效的舌-腭接触，维持口腔期食团控制和推进效率，并尽可能保留语音清晰度，是评价半舌重建质量的关键指标[9]。尤其是在半舌切除后，残余舌往往需要承担更多代偿性运动，而重建皮瓣的体积、柔软度、塑形方式及固定位置均会直接影响其功能代偿能力。

因此，半舌缺损修复重建并非单纯追求“体积充填”或“皮瓣轻薄化”，而是强调体积与动度、支撑与灵活性之间的平衡。若修复组织体积不足，可能导致舌-腭接触不良、口腔期食团残留及吞咽推进效率下降；若皮瓣过于臃肿，则可能占据过多口腔空间，限制残舌活动，影响构音、吞咽及精细口腔运动恢复。由此可见，舌癌术后半舌缺损修复重建的关键在于根据缺损范围、口底受累程度、残舌保留情况及术后辅助治疗需求，实现组织量、组织质地和空间构型的精准匹配，并在形态重建基础上最大程度服务于吞咽、构音和生活质量的恢复[10]。

1.2　舌癌术后半舌缺损主要修复重建方法的选择

舌癌术后半舌缺损的修复重建方式主要包括游离皮瓣、局部或区域带蒂皮瓣以及拉拢缝合。

临床方案的选择需综合考虑缺损范围及三维形态、残舌保留情况、口底及下颌骨受累程度、患者全身状况与手术耐受性、既往放化疗史、术后辅助治疗需求以及显微外科技术与医疗资源条件等因素。总体而言，半舌缺损修复重建并不存在适用于所有患者的单一最优方案，其需要在肿瘤安全、创面修复、组织匹配、功能恢复和围手术期风险之间进行个体化权衡。

本文参考牛津循证医学中心（Oxford Centre for Evidence-Based Medicine，OCEBM）证据分级体系[11]，依据纳入研究的设计类型对相关证据进行分级，以期对临床应用较广且具有代表性的修复重建方式进行归纳比较。其中，Ⅰ级证据主要指随机对照试验的系统综述或高质量Meta分析；Ⅱ级主要包括随机对照研究及前瞻性比较研究；Ⅲ级主要包括非随机对照研究、回顾性队列研究及病例对照研究；Ⅳ级主要包括病例系列、病例报告及低质量回顾性研究；Ⅴ级则主要为专家意见或机制推测。鉴于部分修复方式同时存在不同研究设计类型的报道，本文采用证据区间的形式，对相关研究证据的整体强度及层级分布进行综合描述。

1.2.1　游离皮瓣　综合现有研究及临床实践，前臂桡侧皮瓣（radial forearm free flap，RFFF）和股前外侧皮瓣（anterolateral thigh flap，ALT）仍是当前半舌缺损修复重建中最具代表性且适用范围最广的游离皮瓣选择[12]。二者均可用于半舌缺损修复，但重建特点各有侧重。其中，ALT不仅可根据患者体型和穿支解剖情况灵活调整皮瓣厚度和组织量，而且供区隐蔽、供区并发症小，更适用于缺损范围较大、需要较充分组织容量、合并口底或邻近软组织缺损以及强调供区隐蔽性、美学需求高的患者；RFFF则更适用于缺损相对较少、需要轻薄柔软组织覆盖、精细塑形及尽量减少皮瓣对残舌运动限制的病例。实际选择时，应结合缺损大小、残舌运动潜力、患者体型、供区条件及术后放疗计划进行综合判断。ALT、RFFF及其余常用于半舌缺损修复重建的游离皮瓣类型、主要特点及其优缺点比较详见表1。

1.2.2　带蒂皮瓣　与此同时，带蒂皮瓣在部分患者中仍具有不可替代的临床价值[26]。其优势主要体现在操作相对简便、手术时间较短、无需显微吻合、对患者全身条件要求较低等方面，尤其适用于高龄、合并严重基础疾病、无法耐受长时间手术或医疗资源受限的病例。然而，不同带蒂皮瓣在组织厚薄、血供可靠性、旋转弧度、可达范围、供区损伤及术后功能影响方面存在明显差异，其临床应用更多强调与患者条件和缺损特点的个体化适配，而不宜简单进行功能优劣排序。常用于半舌缺损修复重建的带蒂皮瓣类型、主要特点、适应证及其优缺点比较见表2。

1.2.3　拉拢缝合　直接拉拢缝合在游离皮瓣和带蒂皮瓣技术普及后，已较少作为半舌缺损的首选方案。其主要优势在于避免移植组织占据口腔空间，减少皮瓣对残舌运动的限制，并可在一定程度上保留残舌活动性，因此部分患者术后早期语音清晰度可能较好[40]。但该方法会造成舌体总体积减少，削弱舌-腭接触能力，导致口腔期食团控制、吞咽推进效率及进食耐受性下降，其吞咽功能结局往往逊于适当体积的皮瓣重建[41]。因此，直接拉拢缝合更适用于缺损范围相对有限、残舌保留较好、舌体活动代偿能力较强的选择性病例；而对于多数需要兼顾组织容量恢复、空间构型重建和长期功能改善的半舌缺损患者，皮瓣修复仍是更主要的临床选择。

2　舌癌术后半舌缺损修复重建常用皮瓣形态改良及其功能结局

近年来，舌癌术后半舌缺损修复重建的研究重点已不再局限于不同皮瓣类型的选择与应用，而是进一步关注皮瓣形态、厚度、分区及空间构型的优化设计。传统皮瓣虽然能够有效封闭创面并恢复一定组织体积，但在模拟舌体复杂三维形态、维持舌-腭接触、促进食团推进以及恢复动态功能方面仍存在不足。因此，针对皮瓣形态进行个体化改良，已成为提升舌癌术后半舌缺损修复重建功能结局的重要方向。这类改良设计的核心在于根据舌尖、舌体、口底及舌根等不同解剖亚单位的功能需求，实现皮瓣组织量与空间构型的精准匹配，从而在传统皮瓣基础上赋予其更明确的功能化重建属性。

2.1　“ABC”皮瓣

ABC皮瓣是专用于半舌切除术术后缺陷的一种股前外侧皮瓣（ALT）的改良设计[42]，其并非采用固定比例设计，而是依据半舌缺损不同解剖亚单位的形态需求，对ALT皮瓣进行区域化分区。其中，A区主要对应舌尖重建，B区对应舌体及口底区域，C区则用于恢复舌根部形态（图1）。术中根据肿瘤切除范围及残余舌组织情况，对各区域

表1　舌癌术后半舌缺损修复重建常用游离皮瓣比较

Table 1　Comparison of commonly used free flaps for hemiglossal defect reconstruction following tongue cancer surgery

Flap (abbreviation)	Tissue characteristics	Major advantages	Major limitations	Functional outcome features	OCEBM level of evidence
Radial forearm free flap (RFFF)	Thin, pliable, and foldable; suitable for shaping[13]; relatively reliable flap harvest	Excellent pliability, suitable for precise reconstruction; reliable vascular anatomy; sensory nerve can be included in the flap design	Donor site is exposed and often requires skin grafting; sacrifice of the radial artery is needed; donor-site morbidity and aesthetic concerns are relatively prominent	Speech and swallowing outcomes are relatively well established, but donor-site burden is relatively high	Ⅱ - Ⅳ
Anterolateral thigh flap (ALT)	Adjustable thickness[14]; abundant tissue volume[15]; fascia and/or muscle can be included	Concealed donor site; primary closure often possible; sufficient tissue volume; suitable for composite reconstruction	Perforator anatomy is variable; flap may be bulky in some patients	Functional outcomes are similar to those of RFFF, with lower donor-site morbidity[16]	Ⅱ - Ⅳ
Medial sural artery perforator flap (MSAPF)	Thin and pliable; long pedicle; good plasticity[17]	Concealed donor site; lower complication rate; suitable for delicate mucosal reconstruction	Flap harvest is technically demanding; its clinical use is still less widespread than RFFF/ALT	Its use has increased in recent years, and its advantages as a thin flap are becoming increasingly evident[17-19]	Ⅲ - Ⅳ
Posterior tibial artery flap (PTAF)	Soft texture and moderate thickness[20]	Good vessel caliber match for anastomosis; relatively concealed donor site	Sacrifice of the posterior tibial artery is required; strict preoperative assessment of lower-limb blood supply is necessary	Can serve as an alternative option, but is used less frequently	Ⅲ - Ⅳ
Superficial circumflex iliac artery perforator flap (SCIP)	Lightweight and thin; thickness can be tailored	Concealed donor site with minimal morbidity; suitable for thin-flap reconstruction[21-22]	Small-caliber vessels and relatively short pedicle; anatomical variation may affect flap harvest	Has advantages in thin and lightweight reconstruction	Ⅲ - Ⅳ
Fibula free flap (FFF)	Osteocutaneous composite tissue	Suitable for combined soft- and hard-tissue reconstruction[23]; can restore mandibular continuity	Not the first choice for isolated hemiglossal defects; excessive soft-tissue bulk may impair function	Mainly valuable for composite defects involving both soft tissue and mandibular defects[24]	Ⅲ - Ⅳ
Latissimus dorsi perforator flap (LDPPF)	Adjustable flap thickness, wide harvestable range[25]	Relatively large vascular caliber; consistent anatomy; relatively concealed donor site	Perforator exposure and dissection are relatively time-consuming; repositioning in the thoracodorsal region is cumbersome; donor-site complications such as seroma may occur in some patients	Capable of accommodating relatively large tissue volume while preserving a certain degree of mobility	Ⅲ - Ⅳ

OCEBM: Oxford Centre for Evidence-Based Medicine

长度、宽度及厚薄进行个体化调整，以提高新舌与原有舌体轮廓之间的匹配度，并改善舌-腭接触及吞咽功能。

与常规 ALT 皮瓣相比，“ABC”皮瓣的优势在于其更强调半舌不同功能区域的差异化重建，而非单纯依赖软组织填充。通过对舌尖、舌体和舌根区域进行分区塑形，该皮瓣有助于恢复新舌的三维外形，改善舌-腭接触，并使吞咽过程中舌根部能够更有效地接近软腭，从而提高口腔期食团推进效率。因此，“ABC”皮瓣在改善术后吞咽功能方面显示出一定优势。

参考OCEBM证据分级体系[11]，其总体证据等级约为Ⅲ级。尽管现有结果提示其在半舌缺损术后吞咽功能恢复方面具有一定优势，但其长期功能获益、适用缺损类型、学习曲线及多中心推广价值仍有待前瞻性、大样本及标准化功能评价研究进一步验证。

2.2　“五点八线”皮瓣(five-point eight-line segment，FIPELS)

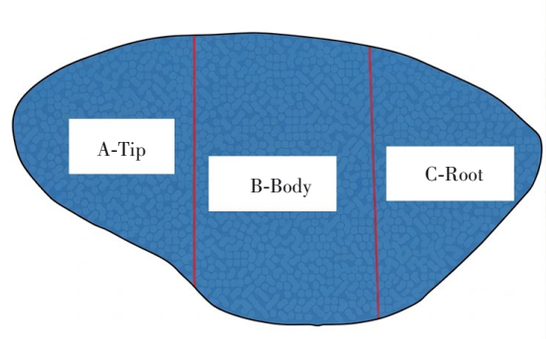
“五点八线”(FIPELS)皮瓣是一种基于半舌真

表2　舌癌术后半舌缺损修复重建常用带蒂皮瓣比较

Table 2　Comparison of commonly used pedicled flaps for hemiglossal defect reconstruction following tongue cancer surgery

Flap (abbreviation)	Tissue characteristics	Major advantages	Major limitations	Functional outcome features	OCEBM level of evidence
Submental island flap (SMIF)	Soft tissue with moderate thickness; adjacent to the oral cavity[27-28]	Reliable blood supply; concealed donor site	Located close to the cervical lymph node dissection field, so oncologic safety must be carefully evaluated[29]; limited tissue volume[30]	Good contour match; suitable for elderly patients or those with limited resources	Ⅲ - Ⅳ
Supraclavicular artery island flap (SCAIF)	Thin and pliable skin flap; easy to shape	Short operative time; in many cases the donor site can be closed primarily; donor-site morbidity is relatively controllable	Distal perfusion and venous drainage are relatively vulnerable; should be used cautiously in patients with previous neck treatment[31]	Particularly suitable for patients with comorbidities or in settings with limited time or resources[32]	Ⅲ - Ⅳ
Facial artery musculomucosal flap (FAMMF)	Thin, mucosa-like, with high tissue compatibility	Texture closely resembles oral mucosa; concealed donor site; rapid recovery[33-35]	Limited length and width; not suitable for large-volume defects	Offers advantages in functional reconstruction and mucosal replacement for small defects[36]	Ⅲ - Ⅳ
Pectoralis major myocutaneous flap (PMMC)	Large tissue volume; relatively bulky	Rapid flap harvest; reliable blood supply; suitable for salvage and complex cases	The flap is bulky and may impair oral function; donor-site appearance and thoracic function may be affected	More suitable for coverage and filling, but less favorable for delicate functional reconstruction[37]	Ⅲ - Ⅳ
Trapezius island myocutaneous flap (TIMF)	Can provide a large amount of tissue; large flap size; long vascular pedicle; relatively large arc of rotation	Suitable for complex or large defects[38]	Bulky flap, vascular variation, and relatively limited clinical application[39]	The flap is relatively thick, and overall functional outcomes are generally modest	Ⅳ

OCEBM: Oxford Centre for Evidence-Based Medicine



Part A forms the tongue tip, part B is used to reconstruct the tongue body and the floor of the mouth, and part C is used to reconstruct the tongue root. The figure is based on the original image from reference[42] (Int J Oral Maxillofac Surg, 2016, 45(6): 726-730). Copyright permission was obtained from Elsevier, and the image was redrawn with the assistance of generative AI (Gemini 2.5); layout adjustments and annotation optimizations were completed using Microsoft Powerpoint version 16.0.14334.20756

Figure 1　Schematic illustration of the "ABC" flap design

图1　"ABC"皮瓣设计示意图

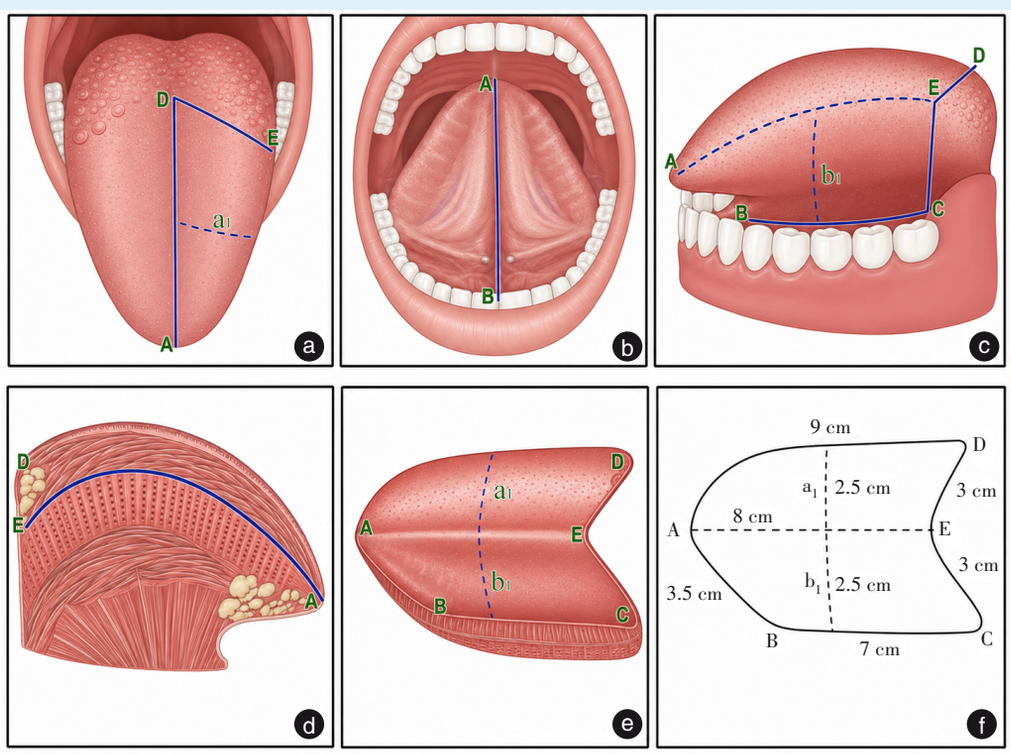
实解剖轮廓的三维几何化皮瓣设计策略[43]。该策略通过动物模型及人类舌部MRI扫描，确定半舌重建中具有代表性的五个关键解剖标志点，即舌尖(A)、舌腹/舌系带前连结点(B)、舌腹/舌系带后连结点(C)、舌背根部内侧转折点(D)及舌背根部外侧角(E)，并进一步确认其相连线段A-B、B-C、C-E、D-E、A-D、A-E的比例关系(图2)。基于上述解剖参数，FIPELS皮瓣能够完成相对精准的二维皮瓣设计，并通过折叠、塑形后重建接近天然半舌形态的三维结构。

与传统经验性皮瓣设计相比，FIPELS皮瓣的核心优势在于将半舌复杂的空间形态转化为可量化、可复制的几何参数，从而提高皮瓣制取和塑形的准确性。该设计有助于减少术中反复修剪皮瓣

所造成的组织浪费和操作时间，同时更好地恢复新舌的形态、体积及空间接触关系。通过重建接近自然舌体的可移动外形和有效组织容量，FIPELS皮瓣可增加新舌与腭部、颊黏膜及牙列之间的接触面积，进而改善口腔期食团控制、吞咽推进及术后外观效果。因此，其并非单纯的皮瓣形状改良方法，而是一种以解剖比例和功能接触为基础的精准化半舌重建方案。

在此基础上，FIPELS皮瓣还可与腭语音矫治器联合应用[44]。通过改善腭部接触面和构音支撑条件，弥补单纯皮瓣修复重建在精细构音方面的不足。这种“皮瓣形态重建+辅助功能矫治”，有望成为半舌缺损术后综合功能恢复的重要方向。

参考OCEBM证据分级体系[11]，其证据等级可列为Ⅱ级。总体而言，FIPELS皮瓣为半舌缺损修复重建提供了一种更具标准化和可重复性的设计思路，尤其在改善吞咽功能和外观重建方面具有较好前景。



a: dorsal view of the tongue. b: ventral view of the tongue. c: lateral view of the tongue. d: schematic longitudinal section of the hemi-tongue, showing the internal structures of the tongue. e: three-dimensional view of the hemitongue. f: two-dimensional “five-point eight-line” flap design template generated from the above anatomical landmarks and measurement parameters, with representative dimensions indicated. A: tongue tip. B: anterior junction point of the ventral tongue and lingual frenulum. C: posterior junction point of the ventral tongue and lingual frenulum. D: medial turning point at the root of the dorsal tongue. E: lateral angle at the root of the dorsal tongue. a1: transverse distance from the lingual midline to the lateral border on the dorsal surface of the hemitongue. b1: distance from the lateral border of the tongue to the ventral tongue-floor-of-mouth junction. The figure is based on the original image from reference [43] (Head Neck, 2019, 41(5): 1359-1366). Copyright permission was obtained from John Wiley and Sons, and the image was redrawn with the assistance of generative AI (Gemini 2.5); layout adjustments and annotation optimizations were completed using Adobe Illustrator 30.2.1.1

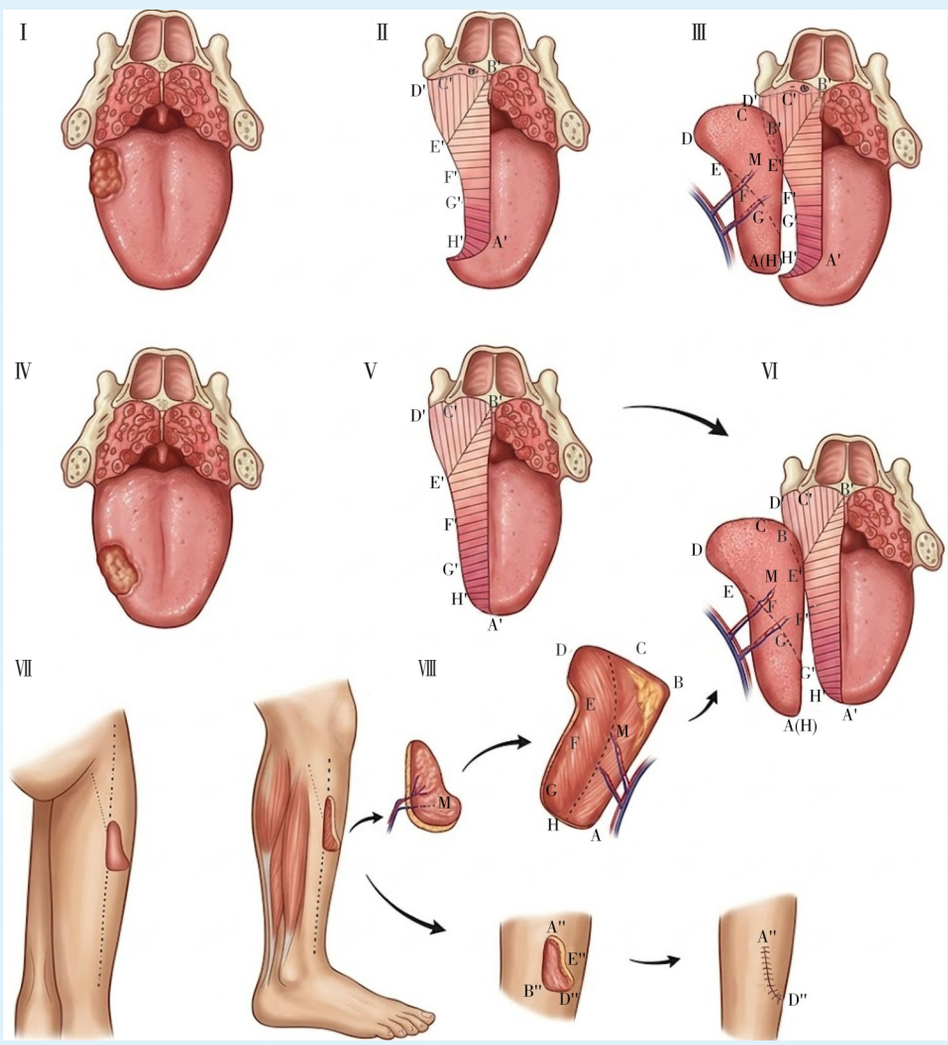
Figure 2　Schematic illustration of the “five-point, eight-line” flap design

图2　“五点八线法”皮瓣设计示意图

2.3　“L型”皮瓣

“L型”皮瓣是对传统股前外侧皮瓣的一种改良型皮瓣，旨在恢复半舌缺损原有舌形态的同时，尽量减少供体部位的损伤，即最大限度地利用皮瓣组织恢复舌缺损[45]。这种皮瓣通过术前对缺损范围及关键解剖标志进行标记和测量（图3），预估舌切除范围，并据此在股前外侧采集尺寸、形状符合术前计划和舌缺损状况的游离皮瓣，转移至舌缺损部位、对齐标记点并吻合血管、缝合创口。供体区在股前外侧皮瓣，这种设计降低了缝合时所需的压力，减少了缝合前修剪组织的需要，因而恢复效果更佳；在舌缺损的舌体区域，该皮瓣形状更接近舌原有形态，且可以重建舌系带，附着力更小，活动性更强。在术后随访中，该皮瓣在吞咽功

能和语音功能方面优于传统ALT。“L型”皮瓣来源于小样本非随机对照研究，依据OCEBM证据分级体系，证据等级为Ⅲ级，其适应证范围及长期功能结局尚缺乏充分证据支持。



Ⅰ-Ⅲ: tongue tip-preserving hemiglossectomy; Ⅳ-Ⅵ: standard hemiglossectomy; Ⅶ-Ⅷ: donor-site closure lines. A: most anterior point of the dorsal tongue defect. B: foramen cecum. C: posterolateral point of the tongue. D: lateral margin of the pharyngeal defect. E: junction between the lingual gingival margin of the posterior teeth and the floor of the mouth. F: posterior point of the ventral tongue. G: lingual frenulum. H: most anterior point of the ventral tongue defect. M: central point of the tongue defect. A′-H′: corresponding landmarks on the flap for points A-H of the tongue defect, respectively. The figure is based on the original image from reference[45] (BMC Surg, 2022, 22(1): 32). Copyright permission was obtained from Elsevier, and the image was redrawn with the assistance of generative AI (Gemini 2.5); layout adjustments and annotation optimizations were completed using Adobe Illustrator 30.2.1.1

Figure 3　Schematic illustration of the “L-shaped” flap design

图3　“L型”皮瓣设计示意图

3　舌癌术后半舌缺损的功能性重建新进展

与传统以创面覆盖和体积填充为主的重建策略相比，舌癌术后半舌缺损的功能性重建更强调在保证肿瘤学安全和创面可靠修复的基础上，尽可能恢复舌体形态、有效容积、空间构型、感觉反馈及一定程度的主动运动能力。舌在吞咽、构音及食团控制中具有高度复杂的神经肌肉协调特征，因此，单纯“填满缺损”并不等同于真正意义上的功能性重建。近年来，随着显微外科、神经修复、功能性肌肉移植及数字化技术的发展，半舌缺损修复重建的理念正由“形态替代”进一步向“功能导向的精准重建”转变。目前普遍认为，影响术后功能结局的关键并不只在于皮瓣是否成活，还包括重建组织与残余舌之间的体积匹配、空间定位、可动性、感觉恢复潜力及术后康复干预等[46]。目前，神经化修复、动力性重建、多维感觉恢复及数字化辅助设计等方向均显示出一定应用前景，但相关研究多处于探索性阶段，证据主要来源于小样本临床研究、回顾性分析或技术报道，高等级前瞻性证据仍相对有限。

3.1　感觉神经修复与感觉功能恢复

感觉功能恢复是半舌缺损功能性重建的重要组成部分，其意义不仅在于恢复新舌的触觉、温度觉等感觉能力，更在于增强患者对食团位置、口腔残留及局部刺激的感知，从而改善口腔期吞咽控制、提高进食安全性，并降低误吸风险。因此，感觉恢复应被视为影响吞咽、构音及生活质量的重要功能环节。

近年来，带感觉神经的游离皮瓣设计及受区感觉神经吻合逐渐受到关注[47]。其主要方法是将皮瓣携带的感觉神经与受区残留感觉神经进行显微吻合，以促进重建舌体的感觉再支配[48-49]。既往研究显示，感觉神经化皮瓣较非神经化皮瓣通常具有更好的感觉恢复表现，部分研究提示其可能改善语音功能[50]。然而，其对吞咽效率、语音清晰度及总体生活质量的长期获益尚无一致结论[6]，这可能与缺损范围、皮瓣类型、受区神经条件、术后放疗及评价方法不统一等因素有关。

因此，当前感觉神经吻合更适合作为半舌缺损功能重建中的“增强策略”，尤其适用于预期生存期较长、残舌功能较好且对口腔期控制和精细感觉恢复要求较高的患者。未来仍需前瞻性、大样本研究结合标准化感觉测试、吞咽和语音评估及患者报告结局，进一步明确其适应证和长期功能价值。

3.2　动力性重建与神经-肌肉单元重建

除感觉恢复外，动力性重建代表了半舌修复由“静态容积重建”向“主动功能重建”发展的重要方向。其核心在于重建可参与运动的神经-肌肉单元，使新舌在具备一定体积和形态的基础上，能够与残余舌、口底肌群及咽部结构协同参与食团推进和构音活动。

近年来，功能性肌肉移植、携带肌肉成分的复合组织瓣及运动神经吻合等策略逐渐用于舌修复重建，旨在赋予重建舌体一定主动运动能力。动力性舌重建在舌活动度、部分语音清晰度及吞咽功能方面可能优于传统静态重建，尤其在较大范围舌切除后的功能改善中更具潜力[51]。

然而，动力性重建技术复杂，对显微外科操作、受区神经条件及术后康复要求较高，且难以完全复制天然舌肌精细而多方向的运动模式。目前相关证据仍以单中心回顾性研究和早期临床探索为主，样本量有限，评价体系尚不统一。因此，对于半舌缺损患者，动力性重建的价值更多在于改善新舌与残余舌的协同运动，而非完全恢复正常舌功能，临床应用仍需根据缺损范围、残舌代偿能力及患者康复配合度进行个体化选择[52]。

3.3　味觉及多维感知功能的保护与恢复

与触觉、温度觉等一般躯体感觉不同，味觉属于特殊感觉，仅靠重建皮瓣的神经再支配难以恢复，其恢复主要依赖含味蕾的残余黏膜、味觉传入通路以及治疗后的功能代偿。Grasl等[53]对舌切除术后患者进行味觉试纸测试及嗅觉测试发现，客观味觉受损较为常见，但部分患者主观味觉及风味感知仍可维持，推测鼻后嗅觉等机制可能参与了术后味觉感知的代偿。

近年临床研究进一步提示，术后味觉结局受到手术范围及综合治疗等多因素共同影响。前瞻性研究显示，口腔癌综合治疗后放疗及舌切除面积增加与味觉障碍风险增加相关[54]；针对半舌切除患者的纵向研究则发现，味觉在术后早期下降后可呈一定恢复趋势，持续吸烟可能延缓恢复，而戒烟与较好的远期味觉恢复相关[55]。上述结果提示，在保证肿瘤学安全的前提下，尽可能保存残余味觉相关组织及味觉传入通路，并减少辅助治疗及其他不利因素造成的进一步损伤，可能有助于术后味觉功能恢复。

除对残余味觉组织及神经通路的保护外，味蕾移植与再生也为舌缺损后的味觉功能重建提供了新的研究方向。Adpaikar等[56]利用小鼠舌后部味觉干/祖细胞构建味蕾类器官，经优化培养后的类器官可整合至受体舌上皮，并维持味觉受体细胞及味觉神经支配，提示味蕾类器官移植可能成为味觉组织再生的重要策略。此外，在大鼠舌缺损模型中，Zhang等[57]发现小肠黏膜下层细胞外基质联合牙龈间充质干细胞或其外泌体，可促进舌乳头恢复、不同类型味蕾细胞再生及局部再神经支配。然而，目前相关研究仍主要停留在动物实验和组织工程阶段，尚缺乏舌癌术后患者中的临床证据，其长期存活、神经整合及实际味觉功能恢复效果仍有待进一步验证。

除传统味觉功能评估外，生物电子技术也为严重味觉损伤后的辅助感知提供了新的思路。2024年有研究利用柔性舌电极结合脑电信号构建味觉接口，对舌癌切除重建后的舌体进行电生理监测，并尝试对五种基本味觉进行解码[58]。该方法为缺乏味蕾的重建舌提供了味觉信息识别的新途径，但目前尚处于味觉信息解码阶段，而非味觉

组织的生物学再生，且仅为小样本概念验证，其临床可重复性及长期获益仍需进一步验证。总体而言，半舌缺损术后的味觉及多维感知恢复仍处于探索阶段，未来可在传统触觉、温度觉评价基础上进一步纳入客观味觉测试及患者主观风味感知评价，以更完整地反映功能重建效果[59]。

3.4　数字化设计与人工智能辅助精准重建

近年来，数字化外科与人工智能技术为半舌缺损的精准化、个体化重建提供了新路径[60]。基于CT、MRI及三维重建的术前建模，可更准确评估缺损体积、舌体曲面及口底空间关系，辅助皮瓣供区选择、组织容量匹配、皮瓣塑形设计和术后形态预测[61]。对于半舌缺损而言，数字化技术的核心价值在于帮助外科医生更精准地判断重建所需组织量及空间构型。

目前，三维体积分析已被用于评估术后皮瓣萎缩规律，并为术前“适度超量重建”提供依据[62]。虚拟手术规划（virtual surgical planning，VSP）和三维打印技术也逐渐应用于舌修复重建[63]，可通过患者特异性模型、切除导板和皮瓣塑形模板，提高术前设计的可重复性及术中定位的准确性[64-65]。

人工智能技术则主要应用于图像分割、缺损体积预测、皮瓣体积估算、术后形态模拟及功能结局预测等方面[66]。理论上，其可整合影像资料、切除范围、皮瓣类型、放疗计划及随访结果，辅助制定个体化重建方案。然而，目前相关应用仍以术前模拟和技术探索为主，其对术后吞咽、语音及生活质量改善的长期价值尚待验证[67-68]。

总体而言，数字化设计与人工智能辅助重建为半舌缺损功能导向性修复提供了重要工具，但现有研究多为小样本或早期探索[69]，参考OCEBM证据分级体系[11]，整体证据等级仍以Ⅳ－Ⅴ级为主。未来需开展多中心、前瞻性研究，并建立统一的影像建模、皮瓣设计及功能评价标准，以明确其临床推广价值。

综上，舌癌术后半舌缺损修复重建的未来发展方向已不再是单纯比较不同皮瓣“能否修复缺损”，而是进一步比较其在体积匹配、感觉恢复、主动运动重建及长期生活质量改善方面的综合获益。神经化修复、动力性重建及人工智能辅助设计分别对应了功能性重建中的“感知恢复”、“运动恢复”和“精准规划”三个层面。尽管现阶段高等级循证证据仍相对不足，但上述策略已展现出由“形态替代”向“精准功能重建”发展的潜力，并可能成为未来舌癌术后半舌缺损功能导向性重建的重要发展方向。

4　舌癌术后吞咽和语音功能的影响因素

舌功能与手术切除范围呈负相关，手术切除范围越大，术后功能越差。舌功能还与肿瘤原发部位相关，相比起原发于舌前1/3的肿瘤，原发于舌根、扁桃体的肿瘤患者术后吞咽、语音功能更差。

修复重建方式也会对术后功能造成影响。相比直接拉拢缝合，皮瓣修复患者的吞咽功能更好，但语音能力往往下降。这可能是因为皮瓣增加了舌体积，能够保持舌与腭接触，从而改善咽部清除率；然而，笨重而无功能的皮瓣限制了残余舌体活动，阻碍发音。相对地，直接缝合虽导致舌体缩小，但舌活动度保存较好，因此语音表现更佳[41, 70]。在不同皮瓣的比较中[50]，术后语音清晰度与吞咽能力差异并不显著[71]，其主要差别集中在供区并发症与美观性方面，其中股前外侧皮瓣（ALT）因供区并发症少及外观满意度高而具有明显优势[72-74]。

放疗是影响术后吞咽和语音功能恢复的重要危险因素。放疗可能导致舌萎缩及皮瓣体积缩小，加剧吞咽困难。研究显示，肿瘤切除范围和放疗均显著增加吞咽障碍风险，尤其当切除涉及舌根时，口腔期与咽期功能障碍更为明显。此外，放射诱导的舌骨上肌与口咽肌纤维化会降低舌控制力和咽部驱动力，从而进一步损害吞咽[75]。语音方面，放疗后语音功能在治疗后1个月最差，随后2~3个月有所改善。放疗剂量与语音结局呈负相关，可能与纤维化和微血管损伤影响伤口愈合相关。与化疗不同，放疗对语音清晰度影响显著，而不同皮瓣类型（包括复合皮瓣与单筋膜皮瓣）对语音结果无显著差异[76]。

神经支配在功能重建中的作用亦受到关注。带感觉神经的游离皮瓣较无神经皮瓣在触觉、痛觉和温觉恢复方面更为优越，但与健侧舌体相比仍存在差距。部分研究提示，皮瓣感觉恢复可能与吞咽和语音功能改善有关，但尚缺乏充分证据证明其临床益处。此外，具有运动神经支配的功能性肌肉移植可部分替代舌运动，增强吞咽与语音能力，但仍需更多临床数据支持[71]。

总体而言，大多数患者在术后早期（1个月内）因手术创伤、水肿及神经损伤表现为严重吞咽困

难和语音障碍，常需依赖管饲或流质饮食。随着伤口愈合，至术后3~6个月，多数患者的吞咽与语音功能可部分恢复[77]。术后早期功能康复训练对恢复起重要作用：术后2周可开始口腔感觉与运动训练、表面肌电生物反馈训练，术后4周逐渐加入呼吸训练与构音训练，有助于改善吞咽及语音功能。

综合现有研究，除时间因素外，影响舌癌术后半舌缺损术后吞咽及语音功能恢复的因素可大致分为缺损范围因素、治疗相关因素及重建相关因素三类。其中，手术切除范围及残舌保留程度是决定功能结局的基础因素，其影响往往大于后续重建方式的差异，决定术后功能恢复的基本上限；放疗则是术后功能恶化的重要不良影响因素，可通过组织纤维化、肌肉萎缩及感觉功能损伤进一步加重吞咽和语音障碍。相比之下，不同皮瓣类型之间的功能差异总体有限，现有研究更多支持组织量匹配、空间构型设计及残舌运动保留对功能恢复的重要性。感觉神经修复和动力性重建等功能性重建策略虽显示出改善感觉反馈及运动功能的潜力，但其长期临床获益仍有待更高质量研究进一步证实。

各因素之间并非彼此独立。大范围切除会增加对皮瓣组织容量及空间塑形的需求，而过度增加皮瓣体积又可能限制残舌运动；放疗可导致皮瓣萎缩和周围组织纤维化，削弱术前体积设计及神经再支配的长期效果；感觉神经修复和动力性重建的获益则受到受区神经完整性、残舌代偿能力、放疗及康复训练的共同影响。因此，临床决策不宜孤立比较某一种皮瓣或某一项技术，而应围绕“缺损范围—残舌条件—辅助治疗—组织匹配—康复干预”进行整体评估。

5　舌癌术后半舌缺损修复重建后的功能评估

舌癌术后半舌缺损修复后的功能评估应围绕吞咽、语音及整体生活质量等核心结局展开。由于术后功能障碍常同时涉及口腔期食团控制、咽期清除、误吸风险、构音清晰度下降及患者主观功能负担，单一指标难以全面反映真实结局[78]。因此，临床评价不宜依赖某一种工具，而应按照“客观检查—标准化分级—患者报告结局”三个层面进行综合评估，以提高结果的系统性、可重复性及不同研究之间的可比性[79]。具体评价方法见表3。

表3　舌癌术后半舌缺损修复重建后功能评估方法

Table 3　Functional assessment methods after hemiglossal defect reconstruction following tongue cancer surgery

Evaluation category	Assessment method	Functional domain	Application
Objective examination	Videofluoroscopic swallowing study (VFSS)	Swallowing	Dynamically evaluates bolus propulsion, residue, and aspiration from the oral phase to the pharyngeal phase, and is used for overall analysis of the swallowing process and abnormal swallowing events[80]
Objective examination	Fiberoptic endoscopic evaluation of swallowing (FEES)	Swallowing	Allows repeated bedside observation of pharyngeal residue, secretion pooling, and laryngeal sensory-related findings, and is suitable for evaluating swallowing safety and pharyngeal clearance[81-82]
Standardized grading	Penetration-aspiration scale (PAS)	Swallowing	Grades the depth of airway invasion by the bolus and whether it is expelled during swallowing, and is used to quantify swallowing safety[83]
Standardized grading	Dynamic imaging grade of swallowing toxicity (DIGEST)	Swallowing	Based on VFSS, comprehensively evaluates swallowing dysfunction in terms of safety, efficiency, and overall severity[84]
Patient-reported outcomes	MD Anderson dysphagia inventory (MDADI)	Swallowing	Assesses the impact of dysphagia on patients' quality of life and reflects the subjective burden of swallowing difficulty[85]
Clinical perceptual assessment	Perceptual evaluation by trained raters	Speech	Evaluates speech clarity and intelligibility through auditory-perceptual judgment, reflecting speech performance in daily communication[86]
Patient-reported outcomes	Speech handicap index (SHI)	Speech	Assesses patients' subjective perception of speech impairment and its psychosocial impact[87]
Patient-reported outcomes	EORTC QLQ-H&N35	Swallowing, quality of life	Complements the assessment of postoperative quality of life in patients with head and neck cancer from dimensions, such as eating, communication, pain, and social participation[88]

EORTC QLQ-H&N35: European Organisation for Research and Treatment of Cancer Quality of Life Questionnaire-Head and Neck 35

其中，VFSS 和 FEES 可作为吞咽功能客观评价的核心方法，用于观察食团推进、咽期清除、残留及误吸情况[89]，PAS、DIGEST 等量表可进一步对吞咽安全性和功能障碍程度进行标准化分级，MDADI、SHI 及头颈癌相关生活质量量表则有助于补充患者对吞咽、语音、社会交流和生活质量的主观感受[90]。因此，半舌缺损修复后的功能评估应强调多维度、标准化和长期随访，以更全面地反映不同重建策略的真实功能获益。

6　总结与展望

综上，舌癌术后半舌缺损修复重建的核心目标是在安全前提下，实现形态恢复与功能重建的统一。当前临床修复策略已由单纯缺损封闭逐渐发展为兼顾组织容量恢复、空间构型优化及功能重建的综合治疗模式。游离皮瓣仍是当前舌癌术后半舌缺损修复重建的主要方式，其中前臂桡侧皮瓣和股前外侧皮瓣应用最广、研究最充分。而改良型皮瓣设计则在各型皮瓣的基础上，进一步强调舌体三维形态重建及舌-腭接触关系优化，在改善功能方面显示出一定优势。与此同时，感觉神经修复、动力性重建、感觉恢复以及数字化、人工智能辅助设计等新策略，正推动舌癌术后半舌缺损重建由传统经验驱动模式向更加精准化、个体化和功能导向的发展阶段迈进。然而，现有研究总体仍以中低等级证据为主，高质量前瞻性研究及长期随访数据仍相对有限。

在功能评估方面，吞咽造影检查、纤维喉镜吞咽评估及相关标准化分级工具仍是评价吞咽安全性与效率的重要手段；语音感知评价、患者报告结局及生活质量量表则为术后长期功能获益评价提供了重要补充。未来仍需进一步推动功能评价指标的标准化，以提高不同研究之间的可比性，并为新型重建策略的临床验证提供统一评价基础。

值得注意的是，当前数字化设计、人工智能辅助重建及神经功能重建等新兴技术虽已展现出良好的应用前景，但其临床推广仍面临诸多挑战。数字化与人工智能辅助重建高度依赖高质量影像数据、标准化缺损描述及大样本数据库支持，而目前不同中心之间的影像采集标准、功能评价指标及随访体系尚未统一，限制了相关模型的泛化能力与临床应用价值。神经化修复及动力性重建则受到手术复杂度高、学习曲线长、手术时间增加以及长期功能获益证据不足等因素制约，目前仅应用于部分具备条件的医疗中心。

未来，临床转化可按照标准化、前瞻性验证和临床实施三个阶段推进。首先，建立标准化功能评估体系，设立统一的半舌缺损分类、影像采集规范、皮瓣体积测量方法及核心功能结局集，并设置一致的术前和术后随访时间点；其次，依托多中心数据库，对数字化设计和人工智能模型开展独立外部验证，并通过前瞻性、注册性比较研究评价其相较于传统经验设计在手术时间、组织匹配、吞咽、语音和生活质量方面的增量获益。对于神经功能重建，应进一步规范供受区神经选择、吻合方式、感觉及运动评价方法和术后康复方案，明确获益人群。最终，还需评价相关技术的学习曲线、成本效果、设备依赖性及其与现有临床工作流程的兼容性，形成可复制的患者选择标准和诊疗路径，推动半舌重建由技术可行性探索逐步转向真实临床获益验证。

【Author contributions】 Huang ZQ was responsible for the conception and design of the study, supervision of the overall research direction, overall guidance of the manuscript, and manuscript writing, and reviewed and approved the final version of the manuscript. Yuan Y was responsible for conducting the study, data collection, data organization and analysis, and manuscript preparation. Huang ZX contributed to the study design and implementation, and provided guidance on data analysis and critical revision of the important academic content of the manuscript. All authors have read and approved the final manuscript for submission.

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