[DOI]10.12016/j.issn.2096-1456.202550228

· 专家论坛 ·

无牙颌数字化种植外科进展

吴轶群，　汪文颖

上海交通大学医学院附属第九人民医院口腔第二门诊　上海交通大学口腔医学院　国家口腔医学中心　国家口腔疾病临床医学研究中心　上海市口腔医学重点实验室　上海市口腔医学研究所，上海（201999）

【摘要】 无牙颌患者因牙槽骨广泛吸收、口颌解剖结构改变及咬合关系缺失，使种植治疗在方案设计与术中实施方面面临显著挑战。传统手术依赖术者经验，缺乏标准化流程与可视化支持，导致种植体定位误差大、修复效果可预测性差。近年来，数字化技术在无牙颌种植外科中的应用不断拓展，贯穿术前、术中至术后各阶段，推动治疗模式由经验性操作向数据驱动转变。在术前阶段，通过融合锥形束计算机断层扫描、口内扫描、面部扫描等多模态数据实现虚拟患者建模、辅助精确诊断与数字化种植规划。术中，可借助个性化导板、动态导航及种植机器人实现高精度植入操作。上述技术显著提升了无牙颌种植的精度、安全性与效率，改善患者满意度。本文系统阐述了数字化技术在无牙颌种植外科中的关键应用与阶段性成果，分析其在提升术式可控性、标准化及个性化治疗方面的价值，同时指出当前仍存在设备依赖高、流程整合度不足、临床循证证据有限等问题。结合人工智能、多模态影像融合与手术机器人技术的快速发展，本文展望数字化无牙颌种植外科未来向智能化、一体化与远程化方向的持续演进。

【关键词】 无牙颌；　数字化种植；　术前规划；　虚拟种植设计；　三维成像；　计算机辅助设计；　数字导板；　动态导航；　机器人；　人工智能

微信公众号

【中图分类号】 R78　【文献标志码】 A　【文章编号】 2096-1456（2025）10-0819-08

【引用著录格式】 吴轶群，汪文颖. 无牙颌数字化种植外科进展[J]. 口腔疾病防治, 2025, 33(10): 819-826. doi:10.12016/j.issn.2096-1456.202550228.

Advances in digital implant surgery for edentulous jaws

WU Yiqun, WANG Wenying. Second Dental Center, Shanghai Ninth People's Hospital, Shanghai Jiao Tong University School of Medicine; College of Stomatology, Shanghai Jiao Tong University; National Center for Stomatology; National Clinical Research Center for Oral Diseases; Shanghai Key Laboratory of Stomatology; Shanghai Research Institute of Stomatology, Shanghai 201999, China

Corresponding author: WU Yiqun, Email: yiqunwu@hotmail.com

【Abstract】 Edentulous patients often present with severe alveolar bone resorption, restructured maxillofacial anatomy, and loss of occlusal relationships, making implant-supported rehabilitation technically more challenging—particularly in terms of guide stability, implant positioning accuracy, and prosthesis design. Traditional treatment workflows largely rely on clinician experience, which is inherently subjective and limits the ability to achieve precise, controlled implant placement and predictable restorative outcomes. In recent years, the widespread adoption of digital technologies has brought transformative progress to implantology for edentulous jaws. Innovations span from preoperative imaging and 3D reconstruction, intelligent surgical planning, personalized guide design, dynamic navigation, and robotic-assisted implant placement, to digital prosthesis design and immediate loading protocols. These advancements have markedly improved surgical precision, procedural efficiency, and patient satisfaction. This article systematically reviews the key applications and clinical value of digital technologies across the various stages of implant rehabilitation in edentulous cases. We also highlight current challenges, such as high costs and dependence on specialized equipment. Finally, we explore future directions toward more intelligent and integrated solutions that are driven by advances in artifi-

【收稿日期】2025-05-29；【修回日期】2025-08-28

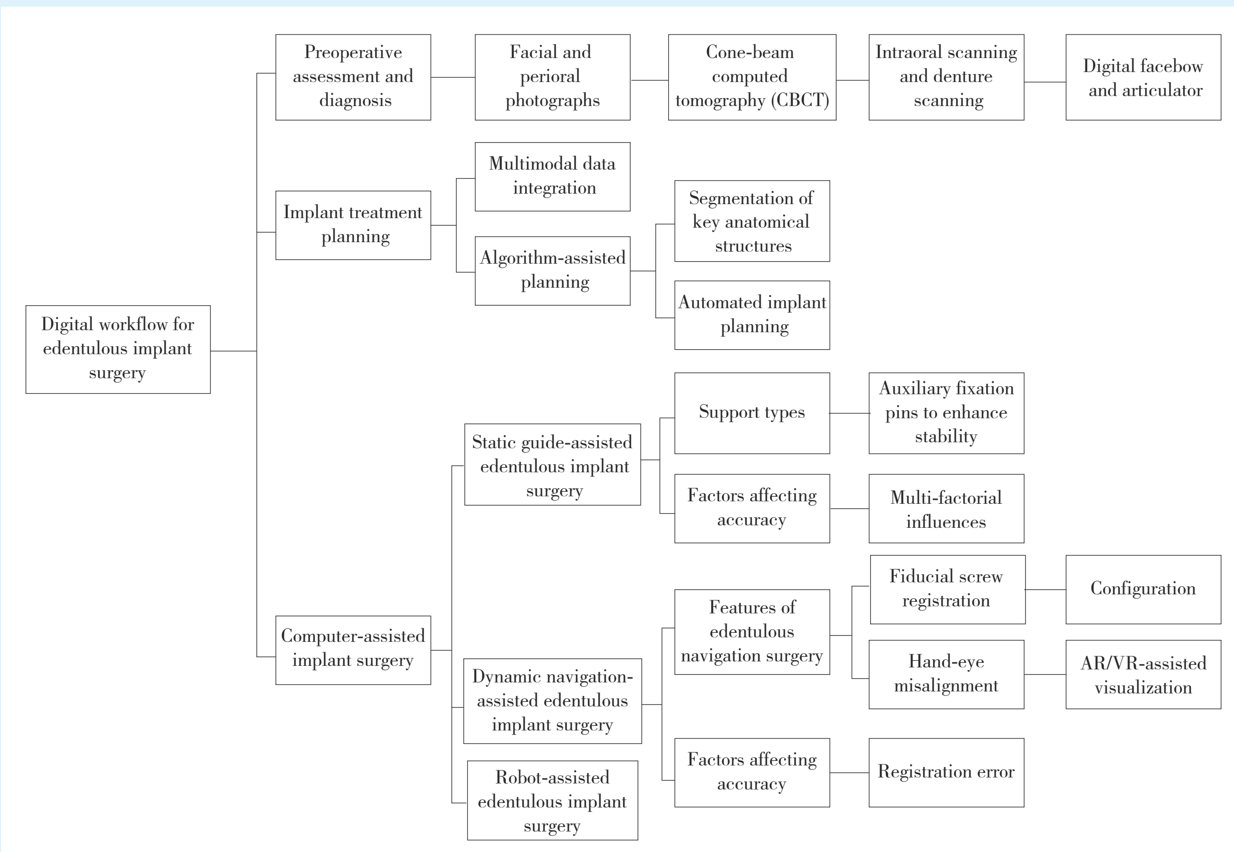
【基金项目】中国医学科学院医学与健康科技创新工程（2019-12M-5-037）

【作者简介】吴轶群，教授，博士，Email：yiqunwu@hotmail.com

cial intelligence, multimodal image fusion, and robotics.
【**Key words**】 edentulous; digital implantology; preoperative planning; virtual implant design; three-dimensional imaging; computer aided design; digital guide plate; dynamic navigation; robot; artificial intelligence
J Prev Treat Stomatol Dis, 2025, 33(10): 819-826.
【**Competing interests**】 The authors declare no competing interests.
This study was supported by the grants from Chinese Academy of Medical Sciences Innovation Fund for Medical Sciences (No. 2019-12M-5-037).

无牙颌患者的种植被视为口腔种植领域中最具挑战性的治疗之一。缺牙时间长、牙槽嵴严重吸收、天然牙标志缺失以及咬合关系紊乱等因素，使该类患者的术前诊断、方案设计与手术实施过程复杂化，对无牙颌种植的精准性与可预测性提出了极高要求[1-4]。传统非数字化流程，包括二维影像评估、石膏模型分析及术者自由手操作等方法适用于多数病例，且已形成较为成熟的操作体系。然而，这一流程高度依赖术者的临床经验与判断能力，缺乏标准量化依据，易在多步骤操作中产生误差累积。在自由手操作下，种植体植入路径完全取决于术者经验判断，缺乏实时引导，面对复杂的解剖结构和有限的可操作空间，种植精度、安全性以及修复与生物力学引导外科的原则难以全面保障。

近年来，以三维成像、计算机辅助设计、数字导板、动态导航及机器人为代表的数字化技术快速发展，从无牙颌患者的术前评估与诊断，到种植方案设计，再到计算机辅助口腔种植手术，数字化技术在口腔种植外科全流程中为无牙颌种植提供了更精准、高效和可控的解决方案（图1），成为推动该领域持续进展的重要动力[5]。



AR: augmented reality; VR: virtual reality

Figure 1　Integration of digital technology throughout the complete workflow of edentulous implant surgery

图1　数字化技术应用于无牙颌种植外科的全流程

1　无牙颌患者的数字化术前评估与诊断

无牙颌患者的数字化评估与诊断为精确的种植规划奠定了基础。借助多种影像学手段和计算机辅助设计技术，可以在术前获取患者详细的解剖数据，进而精确制定个性化的治疗方案。

数字化评估过程包括多源数据整合、咬合关系重建等环节，极大地提高了诊断的准确性和手术实施的可预测性。在数字化评估中，锥形束计算机断层扫描（cone beam computed tomography，CBCT）作为主要的影像技术，为无牙颌患者提供了三维骨组织结构信息。通过 CBCT 可以详细评估患者的骨量、骨密度、骨宽度和高度，帮助医师识别诸如上颌窦、下牙槽神经等关键解剖结构的位置与风险，有助于后续种植体规划[6]。口内扫描和义齿扫描是无牙颌患者数字化诊断的另一个重要组成部分[7]，结合电子面弓与数字粭架，能够帮助重建患者的咬合关系，与后续数字化虚拟排牙结合，从而实现以修复与生物力学为导向的种植手术规划[8]。此外，面部扫描和照片分析可辅助数字化微笑设计，精确制定面部及唇齿美学参数，为患者提供更加符合个性化需求的修复方案[9]。

2　数字化无牙颌种植方案设计

通过术前获取患者的各种数据，如 CBCT、口内扫描、面部扫描等，可以构建虚拟患者，完成种植体的最优设计[10-13]。近年来，计算机算法及人工智能（artificial intelligence，AI）技术的引入使数字化种植方案设计更趋智能化和自动化。在 AI 技术的辅助下，可以实现多模态影像数据的自动分割，精准识别无牙颌患者影像数据中的关键解剖结构，如下颌神经管[14-16]、上颌窦植骨区域[17-18]、颧骨[19]等，辅助医师在无牙颌复杂病例中完成种植体设计。此外，AI 系统还能对牙槽骨密度进行分类评估[20]，预测种植体的初始稳定性，为后续种植位点与术式的选择提供重要依据[21]。部分研究还提出结合增强现实（augmented reality，AR）技术，将 AI 生成的种植路径实时叠加于术者视野中，用于术中导航，提高操作的精度与可视性[22-23]。

通过 AI 辅助的种植方案设计流程，医师不仅能够进行更全面的术前评估与优化设计，还能在规划阶段就对潜在风险进行预判与规避，从而提升无牙颌种植治疗的整体安全性、准确性与可控性。

3　计算机辅助无牙颌种植手术

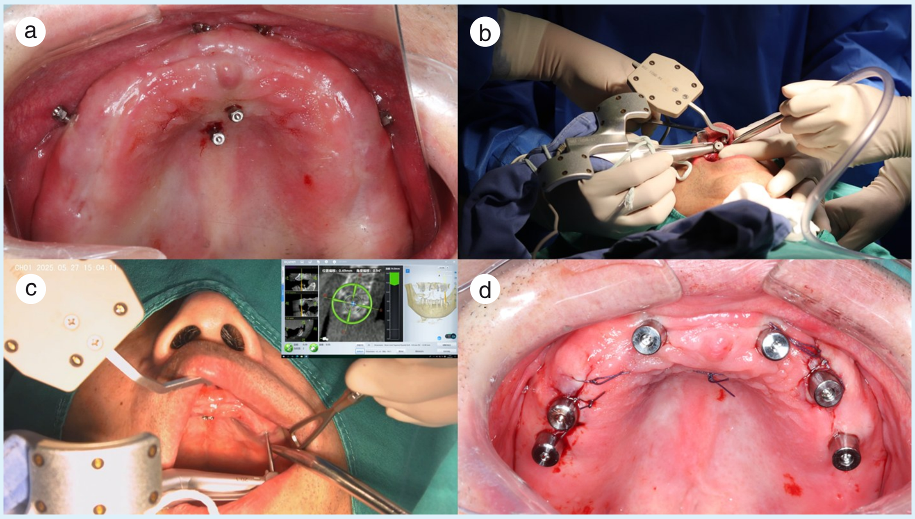
3.1　静态导板辅助无牙颌种植手术

无牙颌静态导板可按照支持方式分为骨支持式导板、黏膜支持式导板和牙支持式导板[24-25]，其中最为常见的是黏膜支持式。但黏膜具有一定的弹性和可让性，单纯黏膜支持的导板稳定性欠佳。为提高黏膜支持式导板的稳定性，可通过安装辅助固位钉来增强导板稳定性[26-28]。对于需要拔除余留牙的终末牙列，也可使用尚稳固的余留牙来辅助支持种植导板，加强导板的稳定性，待行使功能后再拔除这些余留牙。导板手术无法根据术中实时情况调整方案，在特殊病例中也可能受到软组织肿胀或变形的影响，进而影响种植体的精准植入。此外，静态导板辅助无牙颌种植手术的种植精度还受许多因素的叠加影响[29]，例如患者口内软组织的质地及厚度、颌骨的质与量、导板的支持结构、辅助固位装置的设计、套筒设计、3D 打印的精度等[30]。

3.2　动态导航辅助无牙颌种植手术

随着数字化技术不断进步，动态导航系统的引入逐步改变无牙颌种植的治疗方式[31-35]。动态导航系统通过实时反馈钻针位置，可为术者提供一个实时的手术指导。对于无牙颌患者，尤其是在复杂路径（如颧种植体或倾斜植体）的种植手术中，动态导航系统能够显著提升种植体植入的精确度[36-37]。在导航手术的术前准备中，由于无牙颌患者缺少天然牙作为配准的基准，余留牙也不足以支持 U 形管配准装置，因此往往需要术前局部麻醉下先安装配准钉，利用锚定在颌骨上的配准钉来完成导航配准[38-39]。为实现配准钉的精准植入，其位置需在术前基于患者的影像学信息及种植体预设位置进行规划，并据此设计配准钉导板。应确保配准钉的位置避开患者天然牙及颏孔等各种重要解剖结构、患者追踪器的固定区域以及种植体位置。配准钉的分布要尽量分散，避免线性的分布[38, 40-41]。对于上颌无牙颌种植的配准钉分布，建议前牙唇颊侧 2 个配准钉，后牙唇颊侧或上颌结节处 2 个配准钉，腭侧腭中缝附近 2 个配准钉（示例见图 2）；对于下颌而言，由于舌侧血管神经丰富，因此建议在唇颊侧植入至少 4 个配准钉。术中局部麻醉后，在配准钉导板的引导下，植入配准钉。

配准完成后，导航手术的全程中需要保持患者追踪器与患者处于相对静止状态，否则需要重新配准，重新统一患者的实际空间坐标系及 CT 坐



a: placement of six registration screws before navigation surgery; b: pre-surgical registration; c: dynamic computer-assisted implant surgery; d: post-operative photograph

Figure 2 Dynamic computer-assisted implant surgery in the edentulous maxilla

图2 动态导航引导上颌无牙颌种植手术

标系。术中,动态导航系统可以精确定位并计算钻针的位置、角度和深度,并在手术过程中提供实时反馈,帮助术者调整钻针的角度与位置[42-43]。相较于静态导板,动态导航系统的优势在于其灵活性和实时性。术中导航系统通过种植手机上的光学追踪器与导航视觉系统之间的实时数据传输,能够在术者操作过程中提供即时反馈,避免了传统手术中“盲种”的风险。特别是在无牙颌的病例中,由于缺乏天然牙作为定位参考点,传统的自由手操作往往依赖术者的经验完成种植定位。而动态导航则通过实时引导,让即便是经验欠丰富的术者也可以精准地实现术前以修复与生物力学为导向的种植方案。在无牙颌种植手术中,无论是常规种植还是倾斜种植,动态导航系统均能实现高精度种植。本团队针对过去10年国际高质量临床研究做的系统性综述和荟萃分析发现,动态导航引导常规种植手术的平均入点位置偏差为1.07 mm,终点位置偏差为1.27 mm,角度偏差为3.43°[44]。本团队另一篇针对数字化颧种植手术精度的范围性综述结果发现,导航引导颧种植手术的平均入点位置偏差为(1.60 ±0.74)mm,终点位置偏差为(2.27 ±1.05)mm,角度偏差为2.89°±1.69°[45]。

导航种植手术的偏差来源主要分为系统误差、成像误差、配准误差及应用误差[46-47],其中最关键的是配准误差[48-50]。配准钉配准是导航配准的金标准[51-52],但需保证配准时配准钉的位置与术前CT上配准钉的位置一致。骨内配准钉的稳定性受骨质及翻瓣等手术操作的影响,为确保导航系统配准的精度,术者需要在手术配准前确定植入的配准钉是否移位。此外,动态导航存在手眼目标不一致的问题,术者眼睛聚焦导航仪屏幕,而手位于患者口内术区附近,需要医师有一定的手眼协调能力。而且由于术者在导航手术时,注意力容易集中在屏幕上,因此可能会导致患者口内术区附近的其他结构意外损伤。近年数字化技术的发展也进一步解决了这个问题,增强现实技术和虚拟现实技术被引入导航系统,术者在术中佩戴增强现实的眼镜,将导航界面投射在术区,实现手眼目标一致,进一步降低手术风险[53-55]。近年来,摄影测量数字化印模的口外扫描技术在无牙颌种植取模中应用逐渐广泛,相较于传统印模,其精度高、耗时短[56]。以FastMap™为代表的导航光学测量技术(navigated photogrammetry),融合了动态导航与摄影测量数字化印模的优势,可以在导航手术完成后,借助导航系统的视觉系统精确定位种植体位置,进一步简化操作流程,为即刻修复提供高效而精准的解决方案[57]。

3.3 机器人辅助无牙颌种植手术

随着机器人技术的不断成熟,越来越多的种植机器人系统正在逐渐走向临床应用[58-63]。机器人系统通过计算机辅助设计和机械臂的精确控制,实现自动化的钻孔操作,极大地提高了无牙颌种植手术的精度与效率[64-66]。机器人系统能够根据术前规划,自动控制钻孔的深度、角度和位置,精确执行种植体的植入。在All-on-4及颧种植等倾斜种植方案中,稳定的机械臂不受倾斜角度大或手术视野小的影响,可以有效地降低骨损伤或种植体失败的风险[67-69]。无牙颌全口种植常涉及

多颗植体长时间定位与植入，传统操作下术者负荷较高，机器人系统可以通过自动化完成复杂的步骤，显著减轻术者肌肉疲劳与精神紧张，提高手术舒适度与专注度。然而，尽管种植机器人系统在精度和自动化方面表现出色[63, 70-71]，其应用仍面临一些挑战[35, 72-73]。目前的口腔种植机器人大多基于光学定位系统，可见光引导下的视觉导航对手术时光线环境及设备稳定性有较高的敏感性。若患者口内的追踪器发生移动，就会直接影响手术精度。当前机器人系统的适应性还不完全，尤其在面对难以达到的位点、张口受限或解剖结构复杂的病例时，机器人的操作可能受机械臂关节限位影响，需要术者进行额外的干预。此外，目前的机械臂在力量控制及反馈方面仍欠灵活，无法感知患者的骨质情况并灵活做出相应的判断。同时，机器人系统的设备成本高昂，涉及软硬件购置、维护与培训多个环节，术中协作团队需对设备运行逻辑有充分掌握，临床普及仍面临一定门槛。未来，口腔种植机器人系统的发展方向将包括感知与反馈系统的增强（如整合触觉反馈、骨密度检测模块）、结构轻量化与操作界面简化等。借助人工智能算法的辅助，机器人有望实现术中路径自动微调和风险识别，从而进一步提升在复杂无牙颌手术中的应用价值。

4 总结与展望

数字化技术在无牙颌种植中显著提升了手术的精确度和效率，个性化的术前规划和可视化治疗方案使手术过程更加可控，显著改善患者的治疗体验。近年的高质量前瞻性研究表明，与单独使用静态导板或动态导航相比，静态导板和动态导航系统联合使用可提高无牙颌种植的种植精度[74]。然而，数字化技术仍然面临高成本和设备依赖的问题，操作者需掌握多种设备和软件，部分数字化技术例如导航手术具有学习曲线效应[75-77]，需要一定的学习周期。计算机辅助无牙颌种植手术术中的操作完全有赖于术前设计，因此对于术前的规划精度要求极高，但目前多数研究仍局限于小样本、短期随访，尚未系统验证数字化外科对临床疗效的全面提升。

未来，数字化种植外科的发展方向之一是构建统一的一体化数字工作流程平台，实现 CBCT、口内扫描、面部扫描、颌位关系及修复设计等多源数据的高效整合与协同，减少人工操作误差，提升整体效率与精度。随着人工智能和机器学习技术的持续进步，通过多模态影像配准与智能算法，有望实现牙龈、黏膜等软组织的精细数字建模，为复杂无牙颌病例提供更全面的术前评估与方案设计。种植导航与机器人系统的不断发展，将进一步推动手术操作的智能化与自动化，在多学科协作的基础上，为无牙颌种植修复带来更高效、更精准的解决方案。伴随远程控制与外科机器人技术的日趋成熟，未来亦可能实现远程种植设计与导航支持，逐步迈向"远程种植"或"自动植入"，开启个性化、精准化治疗的新篇章。

【Author contributions】 Wu YQ and Wang WY conceptualized and wrote the article. All authors read and approved the final manuscript as submitted.

参考文献

[1] Bosse LP, Taylor TD. Problems associated with implant rehabilitation of the edentulous maxilla[J]. Dent Clin North Am, 1998, 42(1): 117-127.

[2] Messias A, Karasan D, Nicolau P, et al. Rehabilitation of full-arch edentulism with fixed or removable dentures retained by root-form dental implants: a systematic review of outcomes and outcome measures used in clinical research in the last 10 years[J]. J Clin Periodontol, 2023, 50 Suppl 25: 38-54. doi: 10.1111/jcpe.13616.

[3] Ho CC, Jovanovic SA. The "All-on-4" concept for implant rehabilitation of an edentulous jaw[J]. Compend Contin Educ Dent, 2014, 35(4): 255-259.

[4] Maló P, de Araújo Nobre M, Lopes A, et al. All-on-4® treatment concept for the rehabilitation of the completely edentulous mandible: a 7-year clinical and 5-year radiographic retrospective case series with risk assessment for implant failure and marginal bone level[J]. Clin Implant Dent Relat Res, 2015, 17 Suppl 2: e531-41. doi: 10.1111/cid.12282.

[5] Lanis A, Peña-Cardelles JF, Negreiros WM, et al. Impact of digital technologies on implant surgery in fully edentulous patients: a scoping review[J]. Clin Oral Implants Res, 2024, 35(8): 1000-1010. doi: 10.1111/clr.14268.

[6] Jacobs R, Salmon B, Codari M, et al. Cone beam computed tomography in implant dentistry: recommendations for clinical use[J]. BMC Oral Health, 2018, 18(1): 88. doi: 10.1186/s12903-018-0523-5.

[7] Siqueira R, Galli M, Chen Z, et al. Intraoral scanning reduces procedure time and improves patient comfort in fixed prosthodontics and implant dentistry: a systematic review[J]. Clin Oral Investig, 2021, 25(12): 6517-6531. doi: 10.1007/s00784-021-04157-3.

[8] 顾新华. 萎缩无牙颌患者数字化种植即刻修复工作流程[J]. 口腔疾病防治, 2020, 28(12): 749-758. doi: 10.12016/j.issn.2096-1456.2020.12.001.
Gu XH. Digital workflow of immediate implant-supported restoration for atrophic edentulous patients[J]. J Prev Treat Stomatol Dis,

2020, 28(12): 749-758. doi: 10.12016/j. issn. 2096-1456.2020.12.001.

[9] Salloum R. Revolutionizing dentistry: exploring the potential of facial scanners for precise treatment planning and enhanced patient outcomes[J]. J Prosthet Dent, 2024, 132(1): 1-5. doi: 10.1016/j.prosdent.2024.02.036.

[10] Pérez-Giugovaz MG, Sadeghpour M, Revilla-León M. Virtual 3-dimensional representation of a completely edentulous patient for computer-aided static implant planning[J]. J Prosthet Dent, 2023, 129(3): 384-390. doi: 10.1016/j.prosdent.2021.06.038.

[11] Li J, Sommer C, Wang HL, et al. Creating a virtual patient for completely edentulous computer-aided implant surgery: a dental technique[J]. J Prosthet Dent, 2021, 125(4): 564-568. doi: 10.1016/j.prosdent.2020.02.026.

[12] Chen J, Shen Y, Tao B, et al. A fully digital planning protocol for dynamic computer-assisted zygomatic implant surgery based on virtual surgery simulation: a dental technique[J]. J Prosthet Dent, 2024. doi: 10.1016/j.prosdent.2024.08.013.

[13] Zhang Y, Tao B, Wang F, et al. Integrating a mouth opening assessment of virtual patients to prevent intraoperative challenges during treatment[J]. J Prosthet Dent, 2025, 134(3): 562-567. doi: 10.1016/j.prosdent.2023.09.040.

[14] Jiang S, Xu J, Wang W, et al. NURBS curve shape prior-guided multiscale attention network for automatic segmentation of the inferior alveolar nerve[J]. Comput Med Imaging Graph, 2025, 120: 102485. doi: 10.1016/j.compmedimag.2024.102485.

[15] Ntovas P, Marchand L, Finkelman M, et al. Accuracy of artificial intelligence-based segmentation of the mandibular canal in CBCT [J]. Clin Oral Implants Res, 2024, 35(9): 1163-1171. doi: 10.1111/clr.14307.

[16] Oliveira-Santos N, Jacobs R, Picoli FF, et al. Automated segmentation of the mandibular canal and its anterior loop by deep learning [J]. Sci Rep, 2023, 13(1): 10819. doi: 10.1038/s41598-023-37798-3.

[17] Xi Y, Li X, Wang Z, et al. Automated segmentation of graft material in 1-stage sinus lift based on artificial intelligence: a retrospective study[J]. Clin Implant Dent Relat Res, 2025, 27(1): e13426. doi: 10.1111/cid.13426.

[18] Xu J, Gao J, Jiang S, et al. Automatic segmentation of bone graft in maxillary sinus via distance constrained network guided by prior anatomical knowledge[J]. IEEE J Biomed Health Inform, 2025, 29 (3): 1995-2005. doi: 10.1109/JBHI.2024.3505262.

[19] Tao B, Yu X, Wang W, et al. A deep learning-based automatic segmentation of zygomatic bones from cone-beam computed tomography images: a proof of concept[J]. J Dent, 2023, 135: 104582. doi: 10.1016/j.jdent.2023.104582.

[20] Park CS, Kang SR, Kim JE, et al. Validation of bone mineral density measurement using quantitative CBCT image based on deep learning[J]. Sci Rep, 2023, 13(1): 11921. doi: 10.1038/s41598-023-38943-8.

[21] Sakai T, Li H, Shimada T, et al. Development of artificial intelligence model for supporting implant drilling protocol decision making[J]. J Prosthodont Res, 2023, 67(3): 360-365. doi: 10.2186/jpr.JPR_D_22_00053.

[22] Mangano FG, Admakin O, Lerner H, et al. Artificial intelligence and augmented reality for guided implant surgery planning: a proof of concept[J]. J Dent, 2023, 133: 104485. doi: 10.1016/j.jdent.2023.104485.

[23] Elgarba BM, Fontenele RC, Ali S, et al. Validation of a novel AI-based automated multimodal image registration of CBCT and intraoral scan aiding presurgical implant planning[J]. Clin Oral Implants Res, 2024, 35(11): 1506-1517. doi: 10.1111/clr.14338.

[24] Vercruyssen M, Fortin T, Widmann G, et al. Different techniques of static/dynamic guided implant surgery: modalities and indications[J]. Periodontol 2000, 2014, 66(1): 214-227. doi: 10.1111/prd.12056.

[25] D'Souza KM, Aras MA. Types of implant surgical guides in dentistry: a review[J]. J Oral Implantol, 2012, 38(5): 643-652. doi: 10.1563/AAID-JOI-D-11-00018.

[26] Pessoa R, Siqueira R, Li J, et al. The impact of surgical guide fixation and implant location on accuracy of static computer-assisted implant surgery[J]. J Prosthodont, 2022, 31(2): 155-164. doi: 10.1111/jopr.13371.

[27] Chen X, Yang Z, Wang Y, et al. Fixation pins increase the accuracy of implant surgery in free-end models: an *in vitro* study[J]. J Oral Maxillofac Surg, 2023, 81(5): 593-601. doi: 10.1016/j.joms.2022.12.017.

[28] Wu Q, Lou Y, Sun J, et al. Accuracy of the novel digital non-cross-arch surgical guides with integration of tooth undercut retention and screw-bone support for implant placement in mandibular free-end[J]. BMC Oral Health, 2024, 24(1): 550. doi: 10.1186/s12903-024-04329-z.

[29] Chackartchi T, Romanos GE, Parkanyi L, et al. Reducing errors in guided implant surgery to optimize treatment outcomes[J]. Periodontol 2000, 2022, 88(1): 64-72. doi: 10.1111/prd.12411.

[30] 徐淑兰, 李平, 杨烁, 等. 数字化种植导板手术的精确性: 非手术因素分析及对策的专家共识[J]. 口腔疾病防治, 2024, 32(5): 321-329. doi: 10.12016/j.issn.2096-1456.2024.05.001.
Xu SL, Li P, Yang S, et al. Accuracy of digital guided implant surgery: expert consensus on nonsurgical factors and their treatments [J]. J Prev Treat Stomatol Dis, 2024, 32(5): 321-329. doi: 10.12016/j.issn.2096-1456.2024.05.001.

[31] Pellegrino G, Ferri A, Del Fabbro M, et al. Dynamic navigation in implant dentistry: a systematic review and meta-analysis[J]. Int J Oral Maxillofac Implants, 2021, 36(5): e121-e140. doi: 10.11607/jomi.8770.

[32] Panchal N, Mahmood L, Retana A, et al. Dynamic navigation for dental implant surgery[J]. Oral Maxillofac Surg Clin North Am, 2019, 31(4): 539-547. doi: 10.1016/j.coms.2019.08.001.

[33] Wu Y, Tao B, Lan K, et al. Reliability and accuracy of dynamic navigation for zygomatic implant placement[J]. Clin Oral Implants Res, 2022, 33(4): 362-376. doi: 10.1111/clr.13897.

[34] Rawal S. Guided innovations: robot-assisted dental implant surgery [J]. J Prosthet Dent, 2022, 127(5): 673-674. doi: 10.1016/j.prosdent.2022.03.029.

[35] Liu C, Liu Y, Xie R, et al. The evolution of robotics: research and

application progress of dental implant robotic systems[J]. Int J Oral Sci, 2024, 16(1): 28. doi: 10.1038/s41368-024-00296-x.

[36] Bhalerao A, Marimuthu M, Wahab A, et al. Dynamic navigation for zygomatic implant placement: a randomized clinical study comparing the flapless versus the conventional approach[J]. J Dent, 2023, 130: 104436. doi: 10.1016/j.jdent.2023.104436.

[37] Wang F, Fan S, Huang W, et al. Dynamic navigation for prosthetically driven zygomatic implant placement in extensive maxillary defects: results of a prospective case series[J]. Clin Implant Dent Relat Res, 2022, 24(4): 435-443. doi: 10.1111/cid.13101.

[38] Shen Y, Tao B, Sun Y, et al. The effect of fiducial marker number and configuration on registration error in dynamic implant surgery [J]. Int J Oral Maxillofac Implants, 2023, 38(4): 727-732. doi: 10.11607/jomi.10134.

[39] Al-Jarsha MY, Almezyad O, AlOtaibi N, et al. The accuracy of intraoral registration for dynamic surgical navigation in the edentulous maxilla[J]. Int J Oral Maxillofac Implants, 2024(3): 21-46. doi: 10.11607/jomi.10531.

[40] Fan S, Hung K, Bornstein MM, et al. The effect of the configurations of fiducial markers on accuracy of surgical navigation in zygomatic implant placement: an *in vitro* study[J]. Int J Oral Maxillofac Implants, 2019, 34(1): 85 - 90. doi: 10.11607/jomi.6821.

[41] 赵娅琴, 刘艾芃, 岑峰, 等. 动态实时导航与数字化导板导航牙种植精确度的比较[J]. 口腔疾病防治, 2021, 29(3): 178-183. doi: 10.12016/j.issn.2096-1456.2021.03.006.
Zhao YQ, Liu AF, Cen F, et al. Research on the accuracy of dynamic real-time navigation and digital guide navigation implanting techniques[J]. J Prev Treat Stomatol Dis, 2021, 29(3): 178-183. doi: 10.12016/j.issn.2096-1456.2021.03.006.

[42] 满毅, 周楠, 杨醒眉. 动态实时导航在口腔种植领域中的临床应用及新进展[J]. 口腔疾病防治, 2020, 28(6): 341-348. doi: 10.12016/j.issn.2096-1456.2020.06.001.
Man Y, Zhou N, Yang XM. Clinical application and new progress of dynamic navigation system in the field of oral implantology[J]. J Prev Treat Stomatol Dis, 2020, 28(6): 341-348. doi: 10.12016/j.issn.2096-1456.2020.06.001.

[43] 王跃平, 樊圣祈, 吴轶群. 动态导航系统在口腔种植领域的发展和应用[J]. 口腔疾病防治, 2017, 25(10): 613-619. doi: 10.12016/j.issn.2096-1456.2017.10.001.
Wang YP, Fan SQ, Wu YQ. The application and development of dynamic navigation system in implant dentistry[J]. J Prev Treat Stomatol Dis, 2017, 25(10): 613-619. doi: 10.12016/j.issn.2096-1456.2017.10.001.

[44] Yu X, Tao B, Wang F, et al. Accuracy assessment of dynamic navigation during implant placement: a systematic review and meta-analysis of clinical studies in the last 10 years[J]. J Dent, 2023, 135: 104567. doi: 10.1016/j.jdent.2023.104567.

[45] Wang W, Yu X, Wang F, et al. Clinical efficacy of computer-assisted zygomatic implant surgery: a systematic scoping review[J]. J Prosthet Dent, 2023. doi: 10.1016/j.prosdent.2023.10.032.

[46] Block MS. How to avoid errors when using navigation to place implants - a narrative review[J]. J Oral Maxillofac Surg, 2023, 81(3): 299-307. doi: 10.1016/j.joms.2022.11.003.

[47] Tawil I. How dynamic navigation can improve accuracy and minimize errors[J]. Compend Contin Educ Dent, 2021, 42(8): 430-435.

[48] Wei T, Ma F, Sun F, et al. Assessment of the accuracy of two different dynamic navigation system registration methods for dental implant placement in the posterior area: an *in vitro* study[J]. J Pers Med, 2023, 13(1): 139. doi: 10.3390/jpm13010139.

[49] Wu BZ, Sun F. A registration-and-fixation approach with handpiece adjustment for dynamic navigation in dental implant surgery [J]. Heliyon, 2022, 8(9): e10565. doi: 10.1016/j. heliyon. 2022. e10565.

[50] Wu BZ, Xue F, Ma Y, et al. Accuracy of automatic and manual dynamic navigation registration techniques for dental implant surgery in posterior sites missing a single tooth: a retrospective clinical analysis[J]. Clin Oral Implants Res, 2023, 34(3): 221-232. doi: 10.1111/clr.14034.

[51] Lübbers HT, Matthews F, Zemann W, et al. Registration for computer-navigated surgery in edentulous patients: a problem-based decision concept[J]. J Craniomaxillofac Surg, 2011, 39(6): 453-458. doi: 10.1016/j.jcms.2010.10.021.

[52] Wu Y, Wang F, Huang W, et al. Real-time navigation in zygomatic implant placement: workflow[J]. Oral Maxillofac Surg Clin North Am, 2019, 31(3): 357-367. doi: 10.1016/j.coms.2019.03.001.

[53] Mosch R, Alevizakos V, Ströbele DA, et al. Exploring augmented reality for dental implant surgery: feasibility of using smartphones as navigation tools[J]. Clin Exp Dent Res, 2025, 11(1): e70110. doi: 10.1002/cre2.70110.

[54] Tao B, Fan X, Wang F, et al. Comparison of the accuracy of dental implant placement using dynamic and augmented reality-based dynamic navigation: an *in vitro* study[J]. J Dent Sci, 2024, 19(1): 196-202. doi: 10.1016/j.jds.2023.05.006.

[55] Fan X, Tao B, Tu P, et al. A novel mixed reality-guided dental implant placement navigation system based on virtual-actual registration[J]. Comput Biol Med, 2023, 166: 107560. doi: 10.1016/j.compbiomed.2023.107560.

[56] Ma B, Yue X, Sun Y, et al. Accuracy of photogrammetry, intraoral scanning, and conventional impression techniques for complete-arch implant rehabilitation: an *in vitro* comparative study[J]. BMC Oral Health, 2021, 21(1): 636. doi: 10.1186/s12903-021-02005-0.

[57] Pozzi A, Arcuri L, Laureti A, et al. Image-guided photogrammetry accuracy: *in vitro* evaluation of an implant-supported complete arch digital scanning technology[J]. J Prosthet Dent, 2025, 134(3): 818-828. doi: 10.1016/j.prosdent.2025.03.047.

[58] Su T, Teng W, Chu M, et al. Comparing the accuracies of freehand, static computer-assisted and robot-assisted dental implant placements: an *in vitro* study[J]. Int J Comput Dent, 2024, 0(0): 0. doi: 10.3290/j.ijcd.b4870451.

[59] Shi JY, Liu BL, Wu XY, et al. Improved positional accuracy of dental implant placement using a haptic and machine-vision-controlled collaborative surgery robot: a pilot randomized controlled trial[J]. J Clin Periodontol, 2024, 51(1): 24-32. doi: 10.1111/jcpe.13893.

[60] Qiao SC, Wu XY, Shi JY, et al. Accuracy and safety of a haptic operated and machine vision controlled collaborative robot for dental

implant placement: a translational study[J]. Clin Oral Implants Res, 2023, 34(8): 839-849. doi: 10.1111/clr.14112.

[61] Li Z, Xie R, Bai S, et al. Implant placement with an autonomous dental implant robot: a clinical report[J]. J Prosthet Dent, 2025, 133(2): 340-345. doi: 10.1016/j.prosdent.2023.02.014.

[62] Feng Y, Fan J, Tao B, et al. An image-guided hybrid robot system for dental implant surgery[J]. Int J Comput Assist Radiol Surg, 2022, 17(1): 15-26. doi: 10.1007/s11548-021-02484-0.

[63] Chen J, Bai X, Ding Y, et al. Comparison the accuracy of a novel implant robot surgery and dynamic navigation system in dental implant surgery: an *in vitro* pilot study[J]. BMC Oral Health, 2023, 23(1): 179. doi: 10.1186/s12903-023-02873-8.

[64] Wu Y, Zou S, Lv P, et al. Accuracy of an autonomous dental implant robotic system in dental implant surgery[J]. J Prosthet Dent, 2025, 133(3): 764-770. doi: 10.1016/j.prosdent.2024.07.020.

[65] Li P, Chen J, Li A, et al. Accuracy of autonomous robotic surgery for dental implant placement in fully edentulous patients: a retrospective case series study[J]. Clin Oral Implants Res, 2023, 34(12): 1428-1437. doi: 10.1111/clr.14188.

[66] Wang W, Li X, Yao C, et al. Robotic dental implant placement workflow for edentulous jaws[J]. J Prosthet Dent, 2024. doi: 10.1016/j.prosdent.2024.04.030.

[67] Fan X, Feng Y, Tao B, et al. A hybrid robotic system for zygomatic implant placement based on mixed reality navigation[J]. Comput Methods Programs Biomed, 2024, 249: 108156. doi: 10.1016/j.cmpb.2024.108156.

[68] Chen J, Tao B, Yu X, et al. Accuracy of zygomatic implant placement using task-autonomous robotic system or dynamic navigation: an *in vitro* study[J]. Clin Oral Implants Res, 2025, 36(2): 178-190. doi: 10.1111/clr.14373.

[69] Deng H, Wang J, Liu L, et al. Feasibility and accuracy of a task-autonomous robot for zygomatic implant placement[J]. J Prosthet Dent, 2025, 133(6): 1553. e1-1553. e9. doi: 10.1016/j. prosdent.2023.10.029.

[70] Chen J, Ding Y, Cao R, et al. Accuracy of a novel robot-assisted system and dynamic navigation system for dental implant placement: a clinical retrospective study[J]. Clin Oral Implants Res, 2025, 36(6): 725-735. doi: 10.1111/clr.14420.

[71] Yang W, Weng JL, Sun F, et al. Evaluation of the accuracy of dynamic navigation versus robot-assisted dental implant placement in models with one missing tooth or multiple missing teeth with a free-end: an *in vitro* study[J]. J Dent, 2025, 161: 105962. doi: 10.1016/j.jdent.2025.105962.

[72] Saeed A, Alkhurays M, AlMutlaqah M, et al. Future of using robotic and artificial intelligence in implant dentistry[J]. Cureus, 2023, 15(8): e43209. doi: 10.7759/cureus.43209.

[73] Huang S, Wang Z, Li M, et al. Current status and future perspectives of robot-assisted dental implant surgery[J]. Int Dent J, 2025, 75(3): 1608-1620. doi: 10.1016/j.identj.2025.02.020.

[74] Lorwicheanrung J, Mahardawi B, Arunjaroensuk S, et al. The accuracy of implant placement using a combination of static and dynamic computer-assisted implant surgery in fully edentulous arches: a prospective controlled clinical study[J]. Clin Oral Implants Res, 2024, 35(8): 841-853. doi: 10.1111/clr.14185.

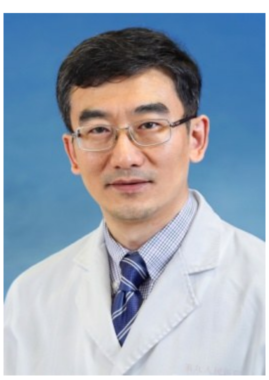
[75] Wang W, Zhuang M, Li S, et al. Exploring training dental implant placement using static or dynamic devices among dental students[J]. Eur J Dent Educ, 2023, 27(3): 438-448. doi: 10.1111/eje.12825.

[76] Wang W, Zhuang M, Tao B, et al. Learning curve of dynamic navigation-assisted zygomatic implant surgery: an *in vitro* study[J]. J Prosthet Dent, 2024, 132(1): 178.e1-178.e12. doi: 10.1016/j.prosdent.2024.03.037.

[77] Zhuang M, Chen J, Tao B, et al. Exploring the learning curve of dental implant placement using a task-autonomous robotic system among young dentists from different specialties-a pilot module study[J]. Clin Implant Dent Relat Res, 2025, 27(1): e13402. doi: 10.1111/cid.13402.

（编辑 周春华，曾曙光）

官网



【作者简介】 吴轶群，口腔医学博士，主任医师，博士生导师，上海交通大学医学院附属第九人民医院口腔第二门诊部主任。中华口腔医学会口腔种植专业委员会副主任委员，上海口腔医学会口腔种植专业委员会主任委员，国际口腔种植协会专家委员会委员（ITI Fellow），国际口腔种植协会中国分会主席，国际口腔种植协会上海奖学金中心主任（ITI Scholarship Centre），上海九院-爱丁堡皇家外科学院口腔种植与修复培训考试中心主任。十三五国家重点研发项目课题负责人，主持国家自然科学基金，国际口腔种植协会（ITI）资助项目等多项国家级、国际级课题项目，研究成果曾获得国家科技进步二等奖（2019）、中华口腔医学科技三等奖（2018）、华夏医学奖三等奖（2016），上海市科技进步一等奖（2010）等。发表论文百余篇，参编著作10余部。