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·综述·

数字化技术在显微根尖手术中的研究进展

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【摘要】 显微根尖手术(endodontic microsurgery,EMS)是通过显微镜提供的放大和照明功能,利用精细器械去除根尖周围的病变组织、切除根尖并严密封闭根管系统,从而促进根尖周组织愈合并尽可能保留患牙的手术。精准定位并切除根尖一直是EMS的难点,数字化技术在EMS中的运用可解决传统EMS中的诸多问题。数字化技术的优势在于可优化手术规划,精确定位引导,提升操作精度。目前在EMS中常用的数字化技术有静态、动态导航技术和口腔手术机器人。静态导航技术通过精确的术前规划制作的个性化导板提高了手术的可预测性,却受限于无法术中调整。动态导航技术则以其实时追踪和术中调整的灵活性见长,但对术者手眼协调能力要求较高,且可能受到手持设备笨重的影响。口腔手术机器人以其高精度、稳定性和实时调整能力,减少了手术中的手部震颤和人为误差,但其临床适用性受限,成本较高。在临床实际运用中,对于不同复杂程度的病例可以采用不同的技术组合,对于相对简单、解剖结构明确的病例,可能静态导航技术就可以满足需求。对于解剖结构复杂的病例,可以先利用静态导航进行初步规划,然后在手术过程中结合动态导航实时引导或者使用口腔手术机器人进行高精度操作。本文对这3种数字化技术在EMS中的工作流程、临床应用现状及其优势和局限性进行探讨,数字化技术的持续发展有望于简化操作流程、提高导航精度、降低操作成本,相信随着技术的不断迭代升级,这些技术将持续优化,不仅能有效突破当前在设备成本、操作复杂性、精准度提升瓶颈等方面的局限,还会进一步拓展应用边界,为牙体牙髓疾病的诊疗提供更加微创、精准、省时的个性化治疗方案。

【关键词】 数字化技术；　计算机引导手术；　显微根尖手术；　静态导航；　动态导航；
手术机器人；　精准化；　微创化
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Research progress on digital technology in endodontic microsurgery

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【Abstract】 Endodontic microsurgery (EMS) is an oral surgical procedure that utilizes the magnification and illumination provided by a microscope. Fine instruments are used to remove periapical diseased tissues, resect the root apex, and tightly seal the root canal system, aiming to promote the healing of periapical tissues and retain the affected tooth whenever possible. Precise localization and resection of the root apex have always been challenging in EMS. The application of digital technology in EMS can address many issues in traditional endodontic microsurgery. Digital technology offers advantages such as optimizing surgical planning, providing precise positioning guidance, and enhancing operational accuracy. Currently, the commonly used digital technologies in EMS include static and dynamic navigation technologies and oral surgical robots. Static navigation technology enhances surgical predictability through precise preoperative planning and guided fabrication, yet is constrained by its inability to adjust during surgery. Dynamic navigation

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technology excels in real-time tracking and intraoperative flexibility but demands high hand-eye coordination from surgeons and may be hindered by bulky handheld devices. Oral surgical robots reduce hand tremors and human error in surgery with their high precision, stability, and ability to adjust in real time, but their clinical applicability is limited and their cost is high. In clinical practice, tailored combinations of these technologies can be applied based on case complexity. For simple cases with well-defined anatomy, static navigation alone may suffice. For complex anatomical cases, static navigation can provide initial planning, supplemented by dynamic navigation for real-time guidance or robotic systems for high-precision execution. This paper discusses the workflow, clinical application status and advantages and limitations of these three digital technologies in EMS. The continuous development of digital technology is expected to simplify the operation process, improve the navigation accuracy, and reduce the operation cost. It is believed that with continuous improvement and optimization, these technologies will effectively break through the current bottleneck of the cost of equipment, operation complexity, and accuracy enhancement. These technologies are also expected to further expand the application boundaries, providing more minimally invasive, precise, and time-saving personalized treatment solutions for endodontic diseases.

【Key words】 digital technology; computer-guided surgery; endodontic microsurgery; static navigation; dynamic navigation; surgical robot; accurate; minimally invasive

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对于根管再治疗失败、严重的根管解剖变异、根管治疗失败且不适合根管再治疗的患牙，显微根尖手术是（endodontic microsurgery，EMS）一种可靠的保存天然牙的治疗方法[1-2]。手术显微镜的运用使术者在治疗过程中获得更清晰明确的视野，提高了手术成功率，但难度较高，且存在不足之处：①依赖术者经验，操作效果受医生技术熟练度影响[3]；②精准控制难度大，易过度去骨或损伤邻近结构[4-5]；③缺乏术中导航工具，突发情况依赖主观判断[6-7]。

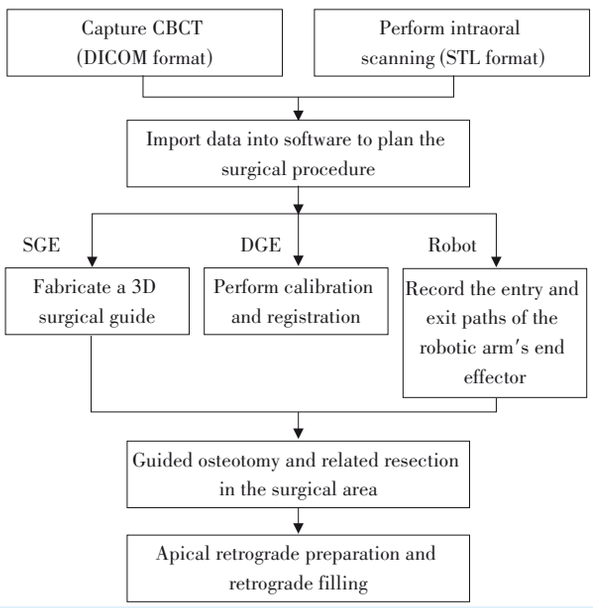
近年来，临床医师逐渐选择使用数字化导航技术辅助完成EMS，依照引导方式的不同可分为静态导航牙髓治疗（static guided endodontics）及动态导航牙髓治疗（dynamic guided endodontics）。静态导航牙髓治疗可辅助精准定位根尖[8-9]，但受制于复杂的术前规划、制作导板的额外时间和成本、缺乏实时的可视化等[10]。动态导航牙髓治疗的应用在一定程度上弥补了静态导航牙髓治疗的不足，可将手术进程可视化于屏幕，术者可根据术区实际情况及时调整操作方向和深度[11-12]。但关键操作仍需临床医生执行，术者在操作过程中的手部震颤和经验不足等引起的偏差可能会影响手术治疗效果[13-14]。随着数字化技术的进一步发展，口腔手术机器人已经成功运用于EMS，在术中通过控制机械臂来执行骨截除和根尖切除，术者可以只专注于实时显示的显示器上，减少了对手眼协调能力的要求，降低了手术的技术敏感性[15]。这3种数字化技术均可辅助术者精准完成EMS，但3种技术各有其优势和不足，本文旨在介绍动静态导航技术、口腔手术机器人在EMS的临床应用现状，为临床医生在选择数字化技术时提供参考。

1　数字化技术的临床操作流程

静态导航牙髓治疗、动态导航牙髓治疗和口腔手术机器人都需要患者在术前行口内扫描和拍摄锥形束CT（cone beam CT，CBCT），数据的精准是保证手术精确、微创、快速实施的前提。CBCT成像出现伪影和变形会导致导板制作和配准过程出现误差，在数据采集过程中必须避免[16-17]。数字化口内扫描技术常用于采集患者的牙列数据，在制取口内模型中，相较于常规的印模材料取模技术，数字化口内扫描技术可以提升患者舒适度、减小扫描误差[18-19]。操作前需将采集的CBCT数据以DICOM格式、口内扫描数据以STL格式输出并导入相关软件重建三维模型，规划手术方案（图1）。

1.1　静态导航牙髓治疗中的3D导板

使用静态导航牙髓治疗时需根据测量的数据设计导板通路的深度、直径和角度[20]，然后进行



SGE: static guided endodontics; DGE: dynamic guided endodontics

Figure 1　Working flow of three digital technologies

图1　3种数字化技术的工作流程图

3D打印。术前将该导板与患者口内进行配对，确定导板的稳定性。术中在导板引导下，准确定位根尖并搭配骨环钻环切骨组织[21]。

1.2　动态导航牙髓治疗术前校准与配准

操作前要安装并校准器械，将患者术前影像与口腔实际解剖位置进行配准。首先，操作器械需注册到动态导航系统，将定位板紧密贴合地安放在操作器械上进行识别和标定，获取其空间位置。其后，把固定器固定在口内不影响手术操作的位置（如对颌或对侧牙列上），再用刚性支架把定位板连接到固定器上，刚性支架的长度和角度要根据患者口腔的解剖结构和手术器械的操作范围进行调整，保证定位板与患者牙列相对静止，从而通过追踪定位板就能追踪患者的真实运动[22]。目前临床上常用配准方式可分为无标记点配准和有标记点配准[23]，基于患者解剖结构的无标记点配准可能产生2～5 mm的误差[24]，而基于人工标记点的有标记配准更准确[25-26]。通过以上配准、标定等流程，显示器上能实时显示术区与操作器械间的空间位置关系，术者可以监控并及时调整，引导进入正确的位点、角度和深度[27-28]。

1.3　口腔手术机器人术前校准与配准

患者确定好体位后佩戴定位板并安装标定追踪装置。用标记探针依次插入带有标记点的定位板完成口内注册，将机械臂末端器械移至预先规划的起始位点，再移出口腔，利用光学追踪系统识别机械臂末端的标记，将路径记录到机器人系统中[29-30]。确保患者头部保持稳定，并与手术机器人对齐。术者通过踏板控制机械臂末端器械进行钻孔备洞预备骨窗并切除根尖，钻孔深度和角度会在显示器上实时显示。在接收到钻孔指令后，机器人会根据术前规划自动将机械臂调整至理想位置，在达到预定深度时自动停止并发出警报。

2　数字化技术在显微根尖手术中的应用

Pinsky等[31]在2007年首次进行静态导板辅助根尖手术的体外研究，证实了静态导航牙髓治疗在提高根尖手术精确性和减少手术并发症风险方面的潜力，为根尖手术的精确定位提供了新的视角。2017年，Connert等[32]利用导板疏通钙化根管，并提出显微导航牙髓治疗（microguided endodontics）的概念。同年，Strbac等[33]利用3D打印手术导板辅助EMS成功治疗了伴有根管超充的根尖周病变患牙。但此时静态导航牙髓治疗在EMS的应用局限于环切骨组织后暴露根尖，根尖切除仍由临床医生在显微镜下用传统车针进行。Giacomino等[34]注意到环钻已成功运用于自体骨移植取骨和移除失败的种植体[35]，该作者团队受此提示，创新性地将导板的钻针改为环钻，并联合3D导板一步实行了去骨、根尖切除和清除病变组织，提出了靶向显微根尖手术（targeted endodontic microsurgery，TEMS）的概念。此概念的提出，进一步优化了静态导航牙髓治疗在EMS的应用，缩短了手术时间并减少了人为因素在手术过程中产生的误差[36]。受此启发，随后多个病例均采取了环钻行静态导航牙髓治疗[21，37]。多项研究[38-39]表明，在EMS领域，静态导航牙髓治疗在手术关键指标的偏差控制上显著优于自由手且手术时间更短，为手术成功与患者术后的良好恢复奠定了坚实基础。

随着静态导航牙髓治疗的运用，其局限性也逐渐凸显，该技术依赖于导板引导，术中难以实时调整[40]。动态导航系统最初被运用于口腔种植手术中[41]，Gambarini等[27]分析该技术在EMS中同样具有优势，并在2019年报道了国际上第一例成功运用动态导航系统实施根尖手术的病例，为后续的动态导航牙髓治疗研究和临床应用提供了参考范例。随后，Fu等[42]临床病例的报道进一步表明了动态导航牙髓治疗在根尖手术的可行性。为了

验证动态导航牙髓治疗在根尖手术应用中的精准度，Dianat等[43]在尸体颌骨上的体外研究结果显示，与自由手（free hand）相比，动态导航牙髓治疗能够更准确地定位和处理根尖病变部位，降低手术风险，缩短手术时间，尤其在处理具有复杂解剖位置的牙根时安全性更高。而与静态导航牙髓治疗相比，动态导航牙髓治疗由于无需使用导板、手术器械相对较短，因此更适用于后牙区和开口受限的患者[33，44]。陈晨等[45]体外研究结果显示，计算机辅助的导航技术能够提高手术的准确性和效率，尤其对于新手医师，这些技术的应用可以显著提升手术表现、缩短手术时间，减少医源性错误。从临床教育角度，数字化技术可辅助医学生更早、更系统地学习和掌握牙体牙髓疾病临床诊疗操作，缩短学习曲线。综上所述，动态导航牙髓治疗的运用，拓宽了手术的适应症，在解剖结构复杂或难以接近的区域，传统根尖手术甚至是利用静态导板实施手术反而可能造成更大的创伤，而动态导航牙髓治疗允许在手术过程中根据实际情况调整治疗方案，提供了更高的灵活性，降低了手术风险[42，46]。

机器人因其卓越的精准度、稳定性、安全性、灵活性和减轻医师术中疲劳等优势已在医疗领域的外科手术中广泛运用，并在口腔医学中也有一定程度的应用[47-48]。2017年，Zhao推出了世界上第一个自主机器人（autonomous robotic，ATR）系统，随后该系统被批准在中国临床使用[49-50]。大量的基础研究和临床试验[51-52]已经证实了ATR系统的准确性和安全性，显示了其在种植手术中的潜在优势。口腔手术机器人可利用红外光学定位与跟踪技术将机械臂末端器械与手术区域建立相对空间关系[53-54]。因此，使用口腔机器人不仅具有动态导航的功能，而且是通过控制和引导机械臂的运动来完成骨截除和根尖切除等关键步骤[55]。目前机器人在EMS的研究较少。Liu等[29]在2024年首次使用机器人实现了精准的根尖切除，标志着EMS领域正式迈入数字化机器人时代。同年，Isufi等[15]报道了运用口腔手术机器人进行根尖切除术的复杂病例，影像学检查见患牙根尖处大面积低密度影且毗邻上颌窦，证明了口腔手术机器人在复杂病例中的可行性。

为了进一步探究口腔手术机器人在临床运用中的准确性和可靠性，苏航等[56]通过利用CBCT和口内扫描两种方法对手术路径的三维偏差进行精度分析，研究结果显示口腔手术机器人能有效地实现根尖手术的可视化和微创化，实现精准的根尖切除。与动态、静态导航技术相比，手术机器人组手术准确性最高，但手术时间较长[57-58]。目前关于口腔手术机器人在EMS中的研究较少，存在局限性，如不同机器人系统性能差异未充分明确、与传统手术和数字化导航技术辅助EMS对比研究不够全面等，且局限于体外研究，未来还需开展更多临床研究以明确机器人辅助EMS的适用性与效果差异，为临床决策提供充分依据。

综上，3种数字化技术均已成功运用于前牙和后牙的EMS，并在解剖结构复杂的病例中体现了其高精准度的优势（表1）。前牙区美学要求高，传统根尖手术切口由水平切口和垂直切口组成，切口设计多依赖术者经验，传统切口易导致牙龈退缩，形成瘢痕，破坏牙列的自然美学外观[59]，数字化技术可辅助进行微创或不翻瓣切口，有利于术后美观和恢复。后牙区根分叉复杂且邻近下颌神经或上颌窦，传统自由手操作风险高，易导致下唇麻木、血管损伤出血等并发症，数字化技术的使用可有效降低后牙区损伤重要解剖的风险，同时后牙区行根尖手术时唇侧作为传统入路，视野开阔，但对于上颌后牙腭根病变切除创伤较大，已有研究借助数字化技术从腭侧入路[34]，可直接精准地到达病变部位，减少了手术创伤。数字化技术的出现优化了手术入路和方法，不仅满足了前牙区美学修复需求，还在后牙区凭借高精准度降低损伤下颌神经、上颌窦等重要解剖结构的风险，并且借助创新的腭侧入路，在处理上颌后牙腭根病变时减少手术创伤，全面提升了后牙手术的精准度和安全性，为EMS带来了革新性的变化。

但数字化技术的术前准备时间较长，流程繁杂，在使用之前医师需提前学习相关技术和软件，且静态导航技术依赖于高精度的个性化导板，而动态导航技术和口腔手术机器人的精准度依赖于术前配准，未来需进一步优化数字化技术的临床准备流程和相关配准技术，以提高其精准度和降低技术敏感性。目前，数字化技术在EMS中使用的器械通常选择在种植中使用的环钻[60]，这可能会导致根端的边缘毛刺或微裂纹[61-62]。目前已有研究使用专为根尖切除设计的Zekrya钻针来执行骨截除和根尖切除，研究表明Zekrya钻针成本效益高，且能创造更光滑的根尖表面[63]。还有研究将超声设备集成到动态导航系统，用于根尖倒预备，

使完全引导EMS具有可行性，提升了手术的精确度[64]。综上，未来研究应聚焦于数字化EMS专用器械及设备的开发，并探索其与其他新兴技术相结合的可行性。

表1　数字化技术在复杂病例中的应用举例

Table 1　Application examples of digital technologies in complex cases

Researcher	Digital technology	Tooth position	Clinical case description
Popowicz W, et al. [37]	SGE	25	Apical low-density lesion adjacent to a pneumatized maxillary sinus
Benjamin G, et al. [21]	SGE	26, 36	Teeth adjacent to critical structures (greater palatine artery, accessory cervical neurovascular bundle, posterior superior alveolar artery)
Giacomino CM, et al. [34]	SGE	17	Intraoperative removal of palatal root lesions via a lateral palatal approach
Li X, et al. [46]	DGE	34, 32, 35, 25	Roots adjacent to mental foramen, implants, inferior alveolar nerve, and maxillary sinus
Fu W, et al.[42]	DGE	16	The root of the affected tooth is closely adjacent to the maxillary sinus, and the palatal root is adjacent to the root of the adjacent tooth
Villa-Machado PA, et al.[65]	DGE	26	Intraoperative elevation of the maxillary sinus in conjunction with piezoelectric osteotomy for removal of the palatal root apices
Fu M, et al.[55]	Surgical Robot	11	A separated instrument approximately 7 mm in length is located beyond the apical foramen of the affected tooth
Isufi A, et al.[15]	Surgical Robot	24, 25	Root of affected tooth adjacent to maxillary sinus

SGE: static guided endodontics; DGE: dynamic guided endodontics

3　数字化技术的优势和缺点

3种数字化技术在EMS运用中各有优劣(表2)。

3.1　共同优势和局限性

数字化技术的共同优势：①提高操作准确性：3种技术均可辅助精准定位根尖，减少去除过多骨组织及损伤重要解剖结构的风险[66-67]；②降低手术难度：可以为新手医师提供明确的操作指引，帮助他们更快掌握手术的关键操作[68-69]；③减少创口暴露在有菌环境的时间，降低术后感染概率[70]。共同局限性：①术前需要行相关检查，增加了患者的治疗费用和术前准备时间；②学习曲线长，需要医师熟练相关设备的操作流程和技术。

3.2　静态导航牙髓治疗的局限性

①部分导板需要嵌入金属或塑料套筒以引导环钻，套筒的长度至少为8 mm[10]，以确保操作精度，对于后牙区治疗或张口受限的患者，导板就位以及环钻的使用受到制约，增加了手术操作难度；②导板精度影响手术效果：导板的精确度受支持形式、打印方式及材料等多种因素的影响，如果导板制作精度不够高，可能会导致手术器械的引导出现偏差[71]；③术中可视性差：由于导板遮挡且碎屑易堆积在套管和环钻之间，术者无法直视术区，一旦出现偏差不能及时发现并处理[72]；④缺乏实时调整：导板制作完成后的位置和角度固定不变，术中出现意外情况时无法及时调整手术路径，影响手术效果[73]。

3.3　动态导航牙髓治疗的优势和局限性

优势：①实时引导与反馈：在手术过程中出现突发状况，如手术区域出血影响视野，或者解剖结构不清晰时，术者可根据显示屏上实时显示的术区状况及时调整操作器械的位置，降低手术风险[74-75]；②手术视野影响小，对开口度要求相对较低：动态导航牙髓治疗主要依靠光学追踪设备对手术器械进行追踪，不需要在口内放置数字化导板而部分遮挡手术视野，更适用于后牙及开口受限的患者[44, 72]。

局限性：①存在定位失误现象：由于配准过程中的误差、手术过程中计算机处理命令延迟而出现医源性错误[72]；②要求较高的手眼协调能力：该技术的学习曲线长，实时显示的视觉信息要求术者的手部动作与之精准匹配，且动态导航牙髓治疗中手机需安装体积较大的红外实时标记装置，术者在操作过程中的手部震颤、术中疲劳、经验不足等引起的偏差可能会影响手术治疗效果[76-77]。

3.4　口腔手术机器人的优势和局限性

优势：①减少人为因素导致的手部颤抖或不稳定[78-79]；②降低手眼协调能力的要求：术中术者可只关注于实时显示术区的显示器，通过操纵机械臂来执行手术关键操作[80-81]；③自动校准：EMS常在局麻下进行，患者很难一直保持静止不动，手术机器人能够识别患者体位变化，使机械臂随着

患者头部的移动自动同步调整，无需重新校准[29]。

局限性：手术中患者需佩戴视觉标记物，如果标记物被污染或被血液遮盖，视觉系统可能无法识别，限制手术的进行[49]。

表2　3种数字化技术在显微根尖手术应用中的优劣势对比

Table 2　Comparison of advantages and disadvantages of three digital technologies in the application of endodontic microsurgery

Category	SGE	DGE	Surgical robot
Technical features	Physical guide + sleeve guidance	Optical tracking + real-time visualization	Robotic arm control + automatic calibration
Mouth opening requirement	High	Relatively low	Relatively low
Hand-eye coordination	High	High	Relatively low (requires experienced surgeon guidance)
Intraoperative real-time adjustment	Not supported	Supported (visual feedback adjustment)	Supported (robotic arm auto-sync adjustment)
Core limitations	Inability to correct deviations	Impact of hand tremors	Dependency on marker stability

SGE: static guided endodontics; DGE: dynamic guided endodontics

4　数字化技术的临床应用选择

在临床实际运用中，数字化技术的使用没有绝对的禁忌证，对于不同复杂程度的病例可以采用不同的技术组合。对于相对简单、解剖结构明确的病例，可能静态导航牙髓治疗就可以满足需求，但如果术中出现意外情况，可以借助动态导航牙髓治疗或口腔手术机器人的优势进行处理。对于复杂的病例，尤其是涉及多根牙、根尖靠近重要解剖结构或者患者解剖结构特殊的情况，临床上可以先利用静态导板定位术区，做好相关标记，然后在手术过程中结合动态导航实时引导或者使用口腔手术机器人进行高精度操作。同时也要注意患者的全身情况，使用静态导航牙髓治疗前，需评估患者开口度、咽反射和周围软组织的情况，确保导板的放置和使用不会影响手术治疗效果。3种技术都为EMS的精确执行和患者安全提供了有效的解决方案，选择最佳方案需综合考虑手术需求、患者状况、资源和术者经验。医师也需要具备更高的技术素养和跨学科知识，以适应新技术的应用和操作。

5　总结与展望

综上，静态、动态导航技术和口腔手术机器人可以弥补传统显微根尖手术的诸多临床不足，具有广阔的应用前景。但未来仍还需要更多的临床试验探究其可靠性、实用性和成本效益。数字化技术的持续发展有望于简化操作流程、提高导航精度、降低操作成本，相信随着技术的不断发展和完善，数字化技术将为牙体牙髓病学的诊疗带来更高的精准度和安全性，推动口腔精准医疗新时代发展。

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