

无套筒静态导航技术在牙髓根尖周病中的应用进展

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[摘要] 无套筒静态导航技术借助3D打印一体化导板,以特制导轨替代传统套筒引导器械,显著提升了根管治疗的精准度和安全性,在处理钙化根管、根尖周炎及纤维桩去除等复杂病例中表现出色,尤其在颌间距离有限的环境中具有显著优势。无套筒静态导航技术通过优化导板设计,提高了冷却效率,降低了手术成本,减少了对牙体组织的损伤,但在材料耐磨性、操作人员对专业软件的使用能力等方面仍存在局限性。本文综述了无套筒静态导航技术的制作流程、临床应用及其优势和不足,并探讨了其在牙髓根尖周病中的应用前景,为临床实践提供参考。

[关键词] 无套筒静态导航技术; 牙髓根尖周病; 根管治疗; 引导牙髓病学; 数字化引导治疗

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Research progress on the application of sleeveless static navigation technology in endodontic disease

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[Abstract] As an innovative endodontic treatment method, the sleeveless static navigation technology has achieved remarkable progress in clinical applications in recent years. This technology uses a 3D-printed integrated surgical guide plate, replacing the traditional sleeve with a specially designed guide rail to precisely guide surgical instruments, thereby enhancing the accuracy and safety of root canal treatment. Research shows that the sleeveless navigation technology excels in handling complex cases such as pulp canal obliteration, periapical periodontitis, and fiber post removal, especially in settings with limited intermaxillary distance. By optimizing the guide plate design, this method improves cooling efficiency, reduces surgical costs, and minimizes damage to dental tissues. However, the sleeveless guide plate is constrained by its material wear resistance and the operating personnel's ability to use specialized software. This paper reviews the manufacturing process, clinical applications, advantages, and disadvantages of sleeveless static navigation technology and explores its potential applications in endodontics to serve as a reference for clinical practice.

[Key words] sleeveless static navigation technology; endodontic disease; root canal treatment; guided endodontics; digital guided therapy

根管治疗是牙髓根尖周疾病的主要治疗方式,但根管钙化显著增加了临床操作难度。根管钙化

的本质特征为第三期牙本质的快速沉积,导致牙髓腔闭塞,常见于牙外伤、自体牙移植、正畸治疗、颌骨骨折及正颌手术后^[1]。这一病理变化给传统根管治疗带来了诸多挑战,如根管口定位困难、疏通钙化段时易发生穿孔及器械分离等。

为了应对这些挑战,锥形束计算机断层扫描

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(cone beam computed tomography, CBCT) 和 3D 打印技术被应用于牙髓根尖周病领域^[2-4]。三维成像技术精确描绘牙齿的根管解剖结构,为复杂病例的治疗提供重要支持^[5-8]。在此基础上,学者提出“引导牙髓病学”^[9-11]这一概念,其主要分为静态导航技术和动态导航技术^[12]。静态导航技术借鉴口腔种植学的引导理念^[13],通过数字化导板引导手术器械,严格遵循预设路径操作,显著降低了技术敏感性,并最大限度地减少对剩余牙体组织的损伤^[14-16]。该技术通过精确的三维成像和数字化导板设计,显著提升了根管治疗的精准度和安全性,尤其在处理钙化根管^[17]、畸形牙^[18]、纤维桩去除^[19-22]及根尖周病^[23]等复杂病例时表现出色。

近年来,静态导航技术在临床应用中取得了显著进展。然而,静态导航技术所使用的带套筒导板存在诸多局限性,如占用额外空间、对后牙区垂直距离有限或张口受限的患者不适用,以及冷却剂不足导致车针过热等问题^[11,24]。为解决这些局限性,无套筒静态导航技术应运而生^[25-26]。该技术摒弃了金属套筒部分,改用特制导轨精确引导手术器械,不仅适用于颌间距离有限的区域,还显著提高了术野的可见度和冷却效果,同时降低了成本^[27-29]。无套筒静态导航技术在种植牙中的应

用已证明其高度准确性^[30-33]。本研究介绍无套筒静态导航技术的制作过程、临床应用及其优势和不足,并探讨其在牙髓根尖周病学中的应用前景,为该技术在临床应用提供一定的参考价值。

1 无套筒静态导航技术概述

无套筒静态导航技术是一种基于数字化设计与增材制造深度融合的创新型手术导板技术。通过整合患者三维影像数据和口内扫描数据,在虚拟手术规划平台上实现器械路径的精准预设计,并借助高精度 3D 打印技术将导航系统与导板主体一次性成型为无活动部件的单体结构^[25]。

1.1 导板制作流程

无套筒静态导航技术的导板设计理念与带套筒静态导航技术有所不同,但制作流程相似^[27-28]。具体而言,无套筒静态导航技术结合患牙 CBCT 的 DICOM 格式数据及口内表面扫描的光学印模数据(STL 文件),在虚拟成像软件中进行数据合并。随后,软件将规划的预备路径叠加到牙齿的扫描图像上,生成用于引导车针到达目标点的导板。最终,通过光固化树脂 3D 打印技术完成导板的制作(图 1)。

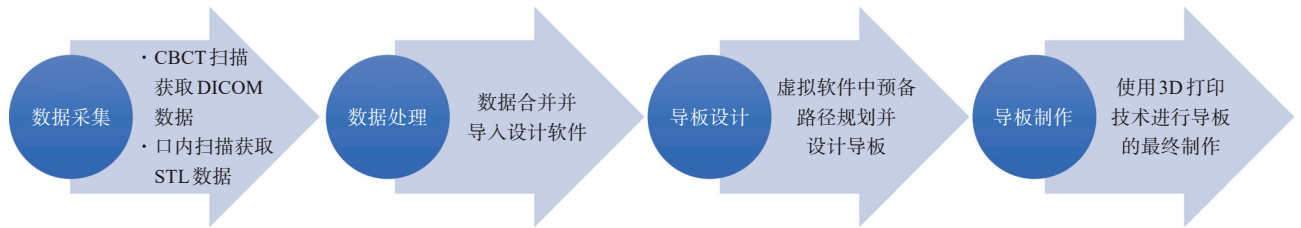


图 1 无套筒静态导航手术导板制作流程

Fig 1 Manufacturing process of sleeveless static navigation surgery guide plate

1.2 工作流程

无套筒静态导航技术摒弃了金属套筒,转而使用两个特制的导轨。导轨根据临床需求采用单颊侧或颊舌两侧对称布局,用以精确引导高速涡轮手机的移动。适配器先安装在手机头部,然后安装在导轨上。当适配器插入导轨后,车针仅能沿直线运动,确保治疗过程中手机的稳定性和精确性^[27]。

2 无套筒静态导航技术在牙髓根尖周病中的应用

2.1 钙化根管

对钙化根管进行根管治疗时,如何准确定位

根管口、获取根管预备的通路是临床治疗的难题。无套筒静态导航技术在解决上述难题方面展现出独特优势。Torres 等^[27]报道了 1 例诊断为钙化根管伴根尖周炎的 46 岁女性患者,采用无套筒静态导航技术成功实现了根管的微创通路,术后 1 年随访显示,患牙根尖周病变区完全骨愈合。Shabnam 等^[34]通过 3D 打印技术设计了一种无套筒静态导航系统,通过无套筒 3D 打印导板和长颈硬质合金车针的联合应用,成功实现了微创开髓与钙化根管的通路建立。Fornara 等^[35]报道了 1 例诊断为下颌尖牙钙化根管伴根尖周炎的 19 岁女性患者,徒手定位根管口失败后,转用无套筒静态导航技术进行精准疏通钙化根管,并采用生物陶瓷封闭

剂行单尖法充填,术后3、24个月的随访影像显示根尖周无明显异常影像,临床症状完全消失。Prabhuji等^[36]介绍了一种创新的无套筒静态导航系统——PriciGuide™,并将其应用于上颌中切牙钙化根管的治疗。该系统通过精确引导微创入路建立,在最大限度保存健康牙本质的同时,为后续根管治疗提供了最佳入路。结果表明,PriciGuide™系统对钙化根管复杂病例的处理效果良好,为提升治疗成功率及改善长期预后提供了新的技术选择。

2.2 根尖周病

对于根尖区根管通路难以建立的病例,显微根尖手术是一种重要的治疗方式。其在口腔手术显微镜辅助下,利用超声及显微器械进行根尖切除、倒预备及倒充填。但该技术受限于牙位、病变部位(如骨皮质肥厚、根尖定位困难、毗邻重要解剖结构)等因素,常面临操作复杂性及损伤风险增高的挑战^[23]。

静态导航技术可有效克服上述挑战,辅助术者精准定位根尖,实现微创去骨并规避损伤风险^[23,37]。2018年,Giacomino等^[38]提出靶向显微根尖手术(targeted endodontic microsurgery, TEMS)概念,即在静态导航技术引导下,基于患牙根尖宽度及毗邻解剖结构,个性化选用匹配环钻,实现靶向去骨和根尖一次性切除,从而简化手术步骤。研究^[38-40]证实,TEMS可精准完成后牙区手术,有效保护上颌窦、腭大动脉及颈神经等重要结构。

Zhao等^[41]通过计算机辅助设计/计算机辅助制造(computer-aided design/computer-aided manufacturing, CAD/CAM)技术设计了无套筒导板,应用于7例上前牙根尖手术患者(试验组),并与7例未使用导板的上前牙根尖手术患者(对照组)的治疗效果进行对比,结果表明,试验组的根尖切除长度偏差和切除角度偏差均显著优于对照组。

Delarue等^[42]采用无套筒静态导航技术对1例孤立性骨囊肿患者进行治疗,术前基于CBCT和牙齿数据进行手术模拟,术中通过牙支持式无套筒导板实现直径3.5 mm的精准骨开窗。术后6个月随访见完全骨再生,2年随访见术区愈合良好且牙髓活力正常。

2.3 纤维桩拆除

纤维桩是根管治疗后修复患牙的常用方法^[43]。然而,当此类患牙需行根管再治疗时,常需先去

除纤维桩以重建通路。尽管目前已开发出多种器械工具以提高桩的拆除效率,如口腔手术显微镜、超声器械及专用桩拆除系统^[44],但在确保牙根结构完整性的前提下完成桩的拆除,仍是一项具有挑战性的任务。在此背景下,无套筒静态导航技术被探索应用于纤维桩的安全拆除。Xue等^[21]报道了一种基于3D打印的无套筒静态导航系统,该系统通过光学扫描仪和CBCT获取目标牙的表面和体积数据,以确定纤维桩去除的虚拟路径,并将其与带有导轨的导板结合,使用钛合金打印出该导航系统,并成功应用于去除目标牙右上中切牙的纤维桩。

3 无套筒静态导航技术的优势

3.1 保护剩余牙体组织

根管预备可导致牙本质结构出现裂纹甚至裂缝^[45-47],不仅损害剩余健康牙体组织的结构完整性,更是牙根纵折的重要诱因之一^[48]。无套筒静态导航技术通过精确的三维路径规划,配合选用小直径车针,能够最大程度地保留剩余健康牙体组织,显著提升牙齿的抗折性能^[16]。Torres等^[27]使用无套筒静态导航技术结合直径1 mm的车针,成功地实现了根管的微创通路预备。另有研究^[49]进一步将车针直径缩减至0.75 mm。上述研究表明,无套筒静态导航技术在保证治疗效果的前提下,为健康牙体组织的保护提供了可量化的解决方案。

3.2 精准度

无套筒静态导航技术在牙髓根尖周病的治疗中展现出卓越的定位精度,不仅可与带套筒静态导航技术相媲美,甚至更胜一筹^[28,50-51]。Torres等^[28]对无套筒静态导航技术下完成的88例严重钙化根管治疗的准确性进行研究,结果显示冠方偏差(0.5 mm)、根尖偏差(0.7 mm)及角度偏差(1.5°)均控制在较低水平,且不同操作者间无显著差异,充分证明了该技术在根管治疗中具备高度精准性。Mo等^[50]通过体外实验分析无套筒静态导航技术去除纤维桩的准确性,结果显示,无套筒静态导航技术的冠方线性偏差(0.19 mm±0.09 mm)、根尖线性偏差(0.54 mm±0.19 mm)和角度偏差(2.67°±1.07°)均显著优于自由手,表明该技术在去除纤维桩中具有高精度性和可靠性。

Prabhuji等^[51]对无套筒静态导航技术、带套筒静态导航技术和自由手进行比较,结果显示,无

套筒静态导航技术在所有的评估维度上均表现最佳,冠方偏差($0.35\text{ mm}\pm 0.16\text{ mm}$)、根尖偏移($0.11\text{ mm}\pm 0.10\text{ mm}$)、角度偏差($0.85^\circ\pm 0.27^\circ$)均低于带套筒导板和自由手。

3.3 后牙区及张口受限区

Hawkins等^[39]指出,带套筒静态导航技术的套筒长度至少达到4 mm方可确保引导路径的准确性。由此可见,该技术受限于套筒的结构限制,在后牙区及张口受限病例中存在明显的应用瓶颈。相比之下,无套筒静态导航技术利用3D打印技术所制作的个性化导板破除了套筒限制,能够适用于后牙区及张口受限的环境,显著提升了手术器械的可及性与可操作性^[52-55]。

3.4 可视化调控

术野可视化是无套筒静态导航技术的重要特征。带套筒导板的结构设计会严重遮挡术区视野,阻碍术者在操作过程中对关键信息的获取。相比之下,无套筒导板的开放式窗口设计^[42,56]允许术者通过以下方式实现动态监测:1)直接观察车针与牙体组织的接触状态;2)实时评估预备深度及角度偏移;3)及时调整冷却剂灌注策略^[21,27-28]。

3.5 冷却效率

带套筒静态导航技术的固有缺陷在于套筒对术区造成物理遮挡,阻碍冷却剂到达车针工作端,导致冷却效率不足^[24,27,57-58]。针对带套筒导板导致的冷却效率不足问题,无套筒静态导航技术因其开放性设计展现出潜在优势。该设计使得冷却剂能够充分到达车针工作端^[29],有效缓解术区热损伤问题。相较于其他封闭式导板,开放式导板能显著降低皮质骨的温度升高^[29]。在口腔种植领域,相较于带套筒静态导航技术,无套筒导航技术能够显著提升术中冷却效率^[59-60]。

此外,车针直径也是影响产热的关键因素。Hussain等^[47]研究表明,较大直径的车针会导致更大程度的温度升高。无套筒静态导航技术因其开放性设计的特点,在车针的选择上具有更高的灵活性,可以选用直径更小的车针^[27]。这一特性结合其固有的冷却优势,可更有效地降低术区产热及热损伤风险。

3.6 成本控制

无套筒静态导航技术在成本控制方面展现出显著优势,主要体现在三个层面。1)材料成本降低:相较于带套筒导板需额外制作套筒及专用车针,无套筒导板的导轨与开放性设计省去了这部

分的制作成本。此外,其配套的手机适配器可重复使用,避免了带套筒导板中需为每位患者单独设计、制作的套筒结构^[28]。2)人力与时间成本优化:带套筒静态导航技术在导板设计与制作流程中,需增加套筒设计、制作及固定步骤。而无套筒静态导航技术得益于3D打印技术及CAD/CAM技术的一体化制作流程,不仅彻底省去套筒固定所需的人力投入与时间成本,而且可以显著缩短导板整体的制作时间^[30]。3)工具通用性提升:无套筒静态导航技术无需考虑车针与套筒内径的精确匹配问题,只需使用临床常规的标准车针。另外,无套筒静态导航技术的手机适配器具有通用性,无需重新制作^[27-28,30]。

4 无套筒静态导航技术的不足

4.1 导板材料性能

无套筒导板的精度与其材料特性密切相关^[61]。无套筒导板的制造材料主要包括树脂、聚乳酸等高分子聚合物和金属材料两类,其中树脂材料占据主导地位^[62]。尽管树脂材料具有良好的可加工性,但其较低的硬度导致耐磨性不足,当车针高速运转时易与导板内壁发生摩擦,产生树脂碎屑。这些碎屑不仅污染术区,还会造成引导通道内径扩大^[62-63],降低定位精度。也有学者^[64]提出导板磨损对精度的影响有限,但该研究使用的车针直径和无套筒导板内径与主流研究存在差异,导致结论的临床适用性存疑。此外,有研究^[21,65]选用金属材料来制作无套筒导板。相较于树脂导板,金属导板具有更高的耐磨性^[66]。但金属导板的引导孔可能存在变形风险,影响手术的稳定性和结果的可靠性^[67]。

4.2 操作人员的技术要求

无套筒静态导航技术的另一个限制在于其对于操作人员的技术要求。复杂根管解剖形态(如弯曲或钙化根管)可能引发引导路径设计偏差,而现有成像设备(如CBCT)与导航系统的分辨率不足可能造成术中执行误差,诱发根管侧壁穿孔或继发性根尖周感染等医源性并发症。因此在使用数字化导板时,操作者需要保持高度的谨慎,即使是具备丰富显微根管治疗经验的医师,也可能发生根管侧穿等情况^[68]。除此以外,除了常规的口腔CAD软件外,操作人员还需掌握工业CAD软件的使用,这些专业的三维设计工具不仅增加

了操作人员学习和使用的负担,还对其专业能力提出了更高要求^[21]。

5 总结与展望

无套筒静态导航技术凭借其在精准度、手术安全性及成本效益方面的显著优势,为牙体牙髓病的临床治疗提供了新的解决方案。该技术通过3D打印技术制作一体化导板,摒弃了传统金属套筒,改用特制导轨引导手术器械,有效克服了带套筒静态导航技术在后牙区及张口受限环境中的局限性,同时优化了冷却效果,降低了手术成本^[69]。在临床上,无套筒静态导航技术已成功应用于钙化根管、根尖周病及纤维桩去除等复杂病例,显著提高了手术的精准性和安全性。此外,该技术不受操作者的经验影响,降低了手术难度^[27,70]。

然而,该技术仍面临多项挑战,导板材料耐磨性不足可能导致碎屑污染术区并影响精度,术前规划和制造过程中的误差也会影响治疗效果^[55,71]。静态导航技术仅适用于直根或弯曲根的直段引导,对复杂根管处理能力有限,且规划过程耗时较长,增加了患者的经济负担^[14,69]。在根尖手术或设计黏膜/混合支持式导板时,需充分考虑软组织厚度,但该技术尚不能完全模拟口内的真实情况。手术区域若存在大范围金属修复体,CBCT扫描时产生的伪影可能会影响导板精度^[23]。无套筒导板因固位需求需覆盖多颗邻牙,难以全程联合橡皮障实现术区有效隔离。近年来提出的冠内导板^[72]、单牙导板^[73-74]等新型设计,因其结构小巧有望解决此问题。此外,尽管该技术的敏感性较低,但临床应用初期仍需进行规范培训以规避潜在的操作失误风险^[27,75]。

未来,静态导板技术可以与动态导航^[76-77]、增强现实(augmented reality, AR)^[78-79]、人工智能(artificial intelligence, AI)^[80-81]、机器人辅助^[82]等技术融合,协同提升手术精度与成功率。动态导航技术可在术中实时调整操作路径,但其效果依赖设备精度、影像配准准确度及术者操作水平^[76-77]。已有学者^[83]提出动静态导航技术联合治疗的相关概念,二者有望在未来实现融合应用趋势;AR通过在头戴式显示器/屏幕上叠加虚拟信息(如手术路径、神经解剖位置),并辅以实时追踪及预警功能,为手术操作提供导航支持。AI在牙髓根尖周

病领域展现出多元化的应用前景,包括根管解剖、根尖病变与根折检测、工作长度测量、牙髓干细胞活力及再治疗成功率预测^[78,80]。AI可实现CBCT影像中髓腔的自动分割,准确率高达95%^[81],未来有望助力疾病诊断、导板设计及入路规划。机器人辅助根尖手术的精准度已显示出超越动静态导航技术的优势^[82],发展潜力显著。然而,技术间的融合是否会引起误差叠加效应仍需关注,亟待更多临床验证。综上,引导牙髓治疗领域仍面临诸多局限与不足,未来的研究应聚焦于开发更高耐磨性的材料,优化导板设计以减少碎屑产生,并简化软件操作流程以降低对操作人员的要求。同时,尚需进一步的临床试验和长期随访研究,以验证该技术的长期疗效和可靠性。随着技术的不断改进,无套筒静态导航技术有望在牙体牙髓病学中发挥更大的作用,为复杂疾病的治疗提供更高效、精准的解决方案。

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