·REVIEW· ·综 述·

脊髓手术D波导航：从监测到决策

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[摘 要] 脊髓手术的核心目标是在最大安全切除病变部位的同时保护神经功能。直接波(direct wave，D波)监测作为评估皮质脊髓束(corticospinal tract，CST)功能完整性的金标准，已从被动监测工具发展为术中主动功能导航系统。为系统梳理D波导航功能的演进与应用，从以下3个方面进行阐述：技术革新(如硬膜下记录)保障了信号的稳定性与定量性；多模态整合(特别是与运动诱发电位协同)实现了突触前与突触后损伤的鉴别诊断；应用范围则已成功拓展至低龄儿童及多种复杂脊髓手术，突破了传统的年龄和病种限制。进一步探讨人工智能预警、影像融合导航等前沿方向，展望D波监测从经验依赖向数据驱动的智能化发展前景，可为提升脊髓手术的精准性与安全性提供理论支撑与实践指引。

[关键词] 直接波；术中监测；功能导航；皮质脊髓束；多模态整合；人工智能

D-wave-guided navigation in spinal cord surgery: From monitoring to decision-making

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ABSTRACT The primary goal of spinal cord surgery is to achieve maximal safe resection of lesions while preserving neurological function. Direct wave (D-wave) monitoring, regarded as the gold standard for assessing the functional integrity of the corticospinal tract (CST), has evolved from a passive monitoring tool into an active intraoperative functional navigation system. To systematically review the evolution and clinical application of D-wave-guided navigation, this article discusses 3 key aspects. First, technological advancements, such as subdural recording techniques, have improved signal stability and enabled quantitative assessment. Second, multimodal integration, particularly in combination with motor evoked potentials, facilitates the differential diagnosis between presynaptic and postsynaptic injuries. Third, the scope of application has been successfully expanded to

收稿日期(Date of reception)：2025-11-13

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基金项目(Foundation item)：国家重点研发计划(2023YFC2412504)。This study was supported by the National Key Research and Development Program of China (2023YFC2412504).

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include very young children and a wide range of complex spinal cord surgeries, overcoming traditional limitations related to age and disease type. Furthermore, emerging directions such as artificial intelligence-based warning systems and image-guided fusion navigation are explored, highlighting the transition of D-wave monitoring from experience-based practice to data-driven intelligence. These developments may provide both theoretical support and practical guidance for improving the precision and safety of spinal cord surgery.

KEY WORDS direct wave; intraoperative monitoring; functional navigation; corticospinal tract; multimodal integration; artificial intelligence

脊髓手术因其功能结构的致密性与不可再生性，被公认为神经外科最具挑战性的领域之一[1-2]。现代手术理念强调在彻底切除病变部位的同时，最大程度保留神经功能并保障患者术后生活质量[3]。术中神经电生理监测(intraoperative neurophysiological monitoring，IONM)技术是实现此目标的关键保障[4]。其中，经颅电刺激运动诱发电位(transcranial motor evoked potentials，tcMEP)所记录的肌肉运动诱发电位(muscle motor evoked potentials，mMEP)虽应用广泛，但易受麻醉等因素干扰，对长期运动功能预后的预测价值有限[5]。相比之下，直接波(direct wave，D波)是经颅电刺激后于脊髓记录的皮质脊髓束(corticospinal tract，CST)快传导轴突的复合动作电位，其信号稳定可靠，振幅与功能完整的CST轴突数量呈线性正相关，被誉为评估CST结构完整性、预测术后长期运动功能的“金标准”[6]。一项于2025年发表、纳入1 079名患者的荟萃分析[7]进一步证实，D波在预测髓内占位永久性运动功能障碍方面的诊断效能显著优于mMEP。也有研究[8]定量地证实了术中D波变化与术后运动功能评分存在显著相关性，强化了其作为预后生物标志物的地位。随着技术进步与策略完善，D波监测已从单一的“损伤警报器”演进为全面的“功能导航系统”。本文旨在系统梳理D波导航在技术演进、多模态整合与应用拓展3大维度的进展，并展望其与前沿技术融合的未来方向。

1 D波功能导航的基石：技术演进与生理学基础

1.1 功能导航的生理学基石：稳定性与可定量性

D波通过“突触前机制”直接沿轴突下传，规避了麻醉药物的抑制[6, 9]。这赋予了其卓越的稳定性(术中变异度通常低于10%)和客观的定量评估能力(振幅与轴突数量线性相关)[1, 10]。术中D波振幅较基线下降50%，在理论上提示约半数功能完好的CST轴突可能受损，为术者量化评估CST损伤提供了独一无二的客观标尺[11]，是实现精准功能导航的物理基础。

1.2 记录技术的革命性进展：从硬膜外到硬膜下

传统硬膜外记录常因高阻抗、脂肪或瘢痕组织导致信号衰减、信噪比低下[12]。近年来，硬膜下电极记录技术取得突破。研究[6]显示，其可将D波记录成功率从不足30%大幅提升至80%以上。将电极置于硬膜下腔能显著降低阻抗、提高基线振幅和信噪比，极大提升了信号可靠性[13]，为在复杂病例中实施精准功能导航奠定了坚实基础。硬膜外与硬膜下记录的D波参数对比见表1。

1.3 预警标准的精细化：从单一阈值到分级管理

基于D波振幅与轴突数量的线性关系，国际公认的报警阈值为振幅较基线下降超过50%[14]。现代监测策略更趋向于分级预警，例如将下降30%~<50%、50%~70%、>70%分别定义为轻、中、重度预警[15]。这种精细化管理的核心价值在于提供了宝贵的“干预时间窗”。一项具有里程碑意义的历史对照研究[16]显示，采用分级预警后，术者在出现轻度预警时即采取干预措施，使患者术后永久性神经功能缺损的发生率从8%降至3%以下。一项回顾性研究[17]也支持这一分级策略的有效性，实现了导航功能从“损伤报警”到“风险预警”的关键前移。

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表1 硬膜外与硬膜下记录的D波参数比较

Table 1 Comparison of D-wave parameters between epidural and subdural recordings

参数	硬膜外记录	硬膜下记录	统计值	*P*	临床意义
成功率	35%(7/20)	85%(17/20)	χ^2=9.23	0.002	可行性显著提升
阻抗/kΩ	4.5±1.2	2.1±0.8	*t*=7.81	<0.001	信号传输效率更高
振幅/μV	12.5±5.6	32.8±10.4	*t*=6.92	<0.001	信号更易识别与分析
信噪比/dB	15.2±3.1	24.7±4.5	*t*=5.78	<0.001	抗干扰能力显著增强

成功率以率和例数表示，其他参数以均数±标准差表示。D波：直接波。

2 功能导航的决策核心：多模态整合与智能解读

2.1 D波与mMEP的协同导航逻辑：突触前与突触后的鉴别诊断

D波的最大价值在于与mMEP等多模式构成协同监测体系[18]。二者联合解读的核心在于对神经损伤进行“突触前”与“突触后”的精准定位与鉴别诊断(表2)。当术中出现mMEP消失但D波保留(振幅>50%基线)时，D波的存在赋予了术者继续谨慎切除的“导航信心”，患者发生永久性运动功能障碍的风险很低(<2%)[19]。反之，当D波出现显著衰减(<50%基线)时，无论mMEP状态如何，均提示CST正遭受结构性损伤的高风险，是强烈的“终止导航”信号[19-20]。最新的荟萃分析[7]量化了这一价值：对于预测永久性运动功能障碍，D波的诊断效能显著高于mMEP(对数诊断比值比3.98 vs 1.89)，其高特异度(95.0% vs 67.6%)是关键。但D波灵敏度低于mMEP(64.2% vs 73.8%)，高特异度意味着当D波报警时，出现永久性损伤的可能性极高(假阳性率低)，这对“终止手术”的决策至关重要。一项大型伞状综述[21]综合分析多项证据后指出，IONM(包括D波)总体上是安全有效的，能够为手术决策提供关键信息。

2.2 针对不同预后模式的精准导航

IONM变化组合能精准预测功能障碍的转归(表2)[7, 22]。若术后即刻功能障碍伴有显著D波变化，其发展为永久性的可能性极高(约87.5%)；若仅伴mMEP变化而D波保留，则更可能是一过性的(恢复率约74.1%)[7]。这凸显了D波在预测长期转归方面的决定性作用[23]。需注意的是，二者各有侧重：mMEP在检测上肢精细运动及单侧CST损伤方面更敏感[7]；而D波作为总体传导功能的指标，对单侧损伤可能不敏感[24]。因此，综合解读方能实现全面导航[25-26]。

表2 D波与mMEP变化组合的临床解读与导航决策

Table 2 Clinical interpretation and navigational decision-making based on combined D-wave and mMEP changes

D波变化	mMEP变化	生理意义解读	预测结局	决策建议
稳定(>50%基线)	稳定	CST结构完整性无损，前角细胞功能正常	运动功能无缺损(PPV>99%)	继续安全切除
稳定(>50%基线)	消失或显著衰减	CST结构完整，前角细胞暂时性功能障碍(如缺血、机械刺激)	一过性运动缺损(恢复率>90%)	暂停操作，寻找原因，通常可恢复后继续
显著衰减(<50%基线)	消失	CST结构性损伤(如轴突受压、缺血)，伴前角细胞功能障碍	永久性运动缺损高风险(PPV为80%~90%)	立即停止手术或彻底改变策略

mMEP：肌肉运动诱发电位；CST：皮质脊髓束；PPV：阳性预测值。

2.3 人工智能赋能导航决策：从经验依赖向数据驱动演进

传统的IONM信号解读高度依赖个人经验，存在主观性和延迟性。人工智能(artificial intelligence，AI)，尤其是深度学习技术，为D波导航的智能化带来了革命性前景[27]。基于循环神经网络(recurrent neural network，RNN)或长短期记忆网络(long short-term memory，LSTM)的模型能对D波信号进行毫秒

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级实时分析，综合评估波形形态、潜伏期微细变化及频谱特征，捕捉人眼难以识别的早期损伤模式[28]。已有研究[29]利用机器学习挖掘出比单一振幅下降阈值更精准的预后预测因子。对IONM数据进行全面、综合的解读，是发挥其最大效用的基础，这一原则同样适用于AI模型的构建[30]。未来，整合多模态IONM数据的AI决策支持系统，有望推动D波导航全面迈向数据驱动的新阶段[31]。

3 功能导航疆域拓展：超越脊髓髓内肿瘤的普适性验证

3.1 挑战极限：低龄儿童脊髓手术中的精准导航

传统观点[32]认为，低龄儿童因CST髓鞘化不完全，难以记录到可靠D波。通过个体化技术适配(如调整刺激电极位置、适度增加刺激强度、优化滤波设置)，这一界限已被成功突破。Fekete等[33]成功为1例10月龄的脊髓栓系患儿实施了稳定的D波监测，术后患儿运动功能完好。近期针对儿童及青少年群体的研究[34]进一步优化了监测策略，并证实了D波在该人群中应用的可行性与价值。这表明，技术参数设置合适时，D波同样能为神经系统发育尚未成熟的儿科患者提供客观、可靠的功能导航，有效弥补了mMEP在该群体中的局限性[35]。

3.2 超越髓内：其他复杂脊髓手术中的宏观导航价值

D波监测的价值已超越经典的脊髓髓内肿瘤(intramedullary spinal cord tumor，IMSCT)切除术，在各类复杂手术中得到验证与拓展。最新的中国专家共识[36]也强调了包括D波在内的多模态IONM对于脊髓胶质瘤等疾病手术安全性的重要意义：1)髓外硬膜内肿瘤切除术。对于大型或腹侧肿瘤，手术牵拉是主要风险。D波振幅变化可客观反映脊髓对牵拉的耐受度，为术者判断牵拉极限提供量化参考，辅助平衡肿瘤切除与功能保护[37-38]。2)脊髓空洞症引流与脊髓栓系松解术。在此类减压手术中，D波可实时评估脊髓切开、粘连松解等操作对CST功能的影响，避免“减压性损伤”，提高手术安全性[39]。3)复杂脊柱畸形矫形手术。在严重侧凸或后凸矫形中，D波对脊髓整体传导功能的宏观、连续评估具有独特价值。D波可以作为mMEP和体感诱发电位的重要补充，尤其在监测因缓慢牵拉或血供变化导致的渐进性脊髓功能障碍方面可能更为敏感[40-41]，为防止过度矫正提供又一道安全防线。

4 未来展望：迈向智能化与融合化的下一代功能导航系统

4.1 影像-电生理融合导航：从“听见”功能到“看见”结构

将术前弥散张量成像(diffusion tensor imaging，DTI)纤维束示踪技术显示的CST三维走行信息，与术中实时获取的D波功能信息进行融合，是未来发展的重要方向[42]。这种“结构-功能”一体化导航系统，有望实现解剖与功能双重引导下的精准操作。

4.2 大数据与精准预后预测

利用机器学习等算法，分析海量术中D波数据(如振幅下降斜率、恢复模式)与患者长期功能结局之间的关系，有望构建精细化的预后预测模型，推动脊髓手术向精准医疗发展[29, 43]。

4.3 技术普及与标准化：导航作用广泛惠及的基石

尽管优势显著，D波监测在国内的普及度和规范化程度仍有待提高[44]。推动该技术的规范化与普及化，形成适合中国国情的专家共识与操作规范[17, 35, 45]，并加强人员培训与标准化流程建设，是确保其导航价值能够稳定、可靠地惠及更多患者的关键[17]。在此过程中，参考和借鉴国际权威组织发布的最新临床实践指南至关重要[46-48]。

5 结　语

D波监测已从一项先进的电生理监测技术，蜕变为脊髓手术中不可或缺的“功能导航系统”。其基于神经生理学的稳定性与定量性、硬膜下记录等技术革新带来的可靠性提升、在多模态整合中展现出的损伤定位与预后预测智慧，以及在多年龄段、多类型脊髓手术中不断拓展的应用疆域，共同奠定了其不可动摇的地位[7, 19, 30]。未来，通过与AI、影像导航等前沿技术的深度融合，D波监测必将引领脊髓外科进入一个更精准、更安全、更智能的新时代[49]。

作者贡献声明：李鹃　文献检索与分析，论文构思、撰写与修改；奚健　论文构思与修改；蒋星军　论文构思、审阅与定稿。所有作者均阅读并同意最终的文本。

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