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麻醉深度监测临床应用研究进展

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摘　要

全身麻醉是由麻醉药物引起的可逆性的无意识状态，在遗忘、镇痛、抑制体动反应的基础上，同时维持自主神经、循环、呼吸与体温调节的稳定。麻醉深度(Depth of Anaesthesia, DOA)过浅或过深可增加术中知晓和术后并发症，因此，对麻醉深度的准确评估有助于对患者进行麻醉过程中的个体化药物管理。目前麻醉深度监测涵盖了中枢神经系统、自主神经系统及运动神经反射等内容，反应意识状态及机体对伤害性刺激的反应，通过专用算法将麻醉深度生理状态的定性评估转换为定量指标。文章描述了麻醉深度监测临床应用研究进展，并讨论了它们未来的发展潜力和可能的应用。

关键词

麻醉深度，脑电图，脑电双频谱指数，自主神经系统，心率变异性

Research Progress on the Clinical Application of Depth of Anesthesia Monitoring

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Abstract

General anesthesia is a reversible state of unconsciousness induced by anesthetic drugs based on amnesia, analgesia, and suppression of motor responses while maintaining stability in autonomic nervous function, circulation, respiration, and thermoregulation. Inadequate or excessive depth of

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anesthesia (DOA) can increase the risk of intraoperative awareness and postoperative complications. Therefore, accurate assessment of DOA is crucial for personalized drug management during the anesthesia process. Currently, DOA monitoring encompasses the central nervous system, autonomic nervous system, and motor reflex responses, reflecting the state of consciousness and the body's reaction to nociceptive stimuli. It converts qualitative assessments of physiological states during anesthesia into quantitative indicators through specialized algorithms. This article outlines the progress in clinical applications of DOA monitoring and discusses their future potential and possible applications.

Keywords

Depth of Anesthesia, Electroencephalogram, Bispectral Index, Autonomic Nervous System, Heart Rate Variability

1. 引言

全身麻醉是由麻醉药物引起的可逆性的无意识状态，在遗忘、镇痛、抑制体动反应的基础上，同时维持自主神经、循环、呼吸与体温调节的稳定[1]。麻醉深度(Depth of Anaesthesia, DOA)过浅或过深可增加术中知晓和术后并发症，因此，对麻醉深度的准确评估有助于对患者进行麻醉过程中的个体化药物管理[2]-[4]。最初，麻醉医生依靠观察病人的体动来辅助判断意识水平，随着科技发展，麻醉深度监测涵盖了中枢神经系统、自主神经系统及运动神经反射等内容，反应意识状态及机体对伤害性刺激的反应，通过专用算法将生理状态的定性评估转换为定量指标[5]。本文描述了麻醉深度监测临床应用研究进展，并讨论了它们未来的发展潜力和可能的应用。

2. 中枢神经系统监测指导麻醉深度

全身麻醉药通过作用于中枢神经系统(大脑皮层、脑干、脊髓)产生全身麻醉作用，从清醒状态到麻醉状态的转变伴随着大脑自发电活动的深刻变化[1]。脑电图(Electroencephalogram, EEG)及其处理后的 EEG (processed EEG, pEEG)提供了个性化麻醉深度监测的潜力。目前，基于脑电信号监测麻醉深度已成为主流的麻醉深度监测技术。

2.1. 脑电图监测指导麻醉深度

脑电图通过在电极实时监测脑神经细胞产生的自发脑电活动中，实现对大脑皮层电位的连续测量，无创地将大脑神经生理与觉醒状态联系起来[6] [7]。脑电图反映了皮层神经元产生的兴奋性和抑制性突触后电位的复合突触活动，是衡量中枢神经系统状态时麻醉深度监测的重要组成之一[4] [8]。皮层和皮层下结构紧密相连，脑电图能够综合反映皮层及皮层下结构的电位活动，一定程度上反映大脑功能状态[9] [10]。原始脑电图根据振荡频率分为不同的波段，包括慢波、δ 波、θ 波、α 波、β 波及 γ 波[10]。麻醉药物通过抑制或阻断大脑皮层的高级活动，降低神经元的放电频率，并同步减缓 EEG 波形的变化，因此，EEG 波形特征性变化与麻醉深度的逐渐增加密切相关[8]。随着全麻深度增加，脑电频率逐渐减慢，同时波幅增大，再至爆发抑制，最终呈等电位线[11]-[13]。然而，脑电信号并不能反映特定麻醉药物作用于大脑中的神经生理学，对儿科人群的麻醉深度监测的准确性存在争议[14]。此外，环境噪声、电力干扰、肌

电图伪影、眼动伪影等许多因素均会干扰脑电信号[15]。

2.2. 脑电图衍生参数指导麻醉深度

pEEG 是在脑电图的基础上产生了经分析计算最终合成的各类大脑状态相关指数，使用专有算法创建从 0 到 100 的无量纲尺度来描述结果，如脑电双频指数(Bispectral Index, BIS)、Narcotrend 监测、熵指数、Neurosense 脑功能监测器，以及中潜伏期听觉诱发电位等[4] [16] [17]。脑电图及 pEEG 为实现个性化麻醉监护提供了新的可能性，能够减少麻醉药物的使用，缩短患者在术后复苏室的停留时间，有助于术后恢复[18]-[20]。

BIS 是时域(爆发抑制比)、频域和高阶谱(双谱)的组合，于 1996 年被 FDA 批准作为麻醉深度的监测仪器，并在全球范围内广泛使用[21]。BIS 来自脑电分析，具体原理是利用数学建模，从前额区域获得的脑电信号中提取功率谱和相位信息，将麻醉深度量化，能较好地监测大脑皮层功能的状态及变化，被认为是目前评估患者意识状态最为敏感、准确的客观指标[22]。BIS 与大多数麻醉药物产生的镇静深度具有相关性，可以降低全身麻醉的高危成人手术患者术中知晓的风险[23]。BIS 的临床应用存在一定局限性，由于 BIS 在数据采集与处理过程中存在时间滞后现象，导致其无法实时反映患者的麻醉深度变化。此外，BIS 监测具有个体差异，并且受到体位、低体温、肌松药和血管活性药物(麻黄碱、肾上腺素和异丙肾上腺素)等术中因素的影响[24] [25]。

Narcotrend 监测采集患者的脑电信号并将信号分为不同的频段，随后对不同频段的信号进行处理和分析，计算出一系列脑电参数，如脑电波形态、波幅和频率等[26]。根据这些脑电参数，Narcotrend 麻醉深度监测将麻醉深度分为清醒、浅镇静、深镇静、普通麻醉、深度麻醉和脑电活动消失 6 个阶段[27]。相对于 BIS 监测，Narcotrend 麻醉深度监测更为简便易用，但相对精确度和敏感度较低，评估阿片类药物的镇痛和镇静效果方面存在局限性，有待进一步探讨与验证[28]。

听觉诱发电位是指声音刺激听觉传导通路经脑干至听觉皮层到达联合皮层的生物电活动，根据潜伏期不同，分为 3 个部分：脑干听觉诱发电位、中潜伏期听觉诱发电位与长潜伏期听觉诱发电位[29]。其中，中潜伏期听觉诱发电位与大多数麻醉药剂量呈依赖性变化，适用于麻醉镇静深度的检测[30]。听觉诱发电位更能实时、快速地监测麻醉深度，能够快速地反应患者意识消失和恢复情况，作为麻醉深度监测指标具有较好的优势[31]。但是，听觉诱发电位测量过程依赖声音刺激，所以比其他麻醉深度监测更容易受到测试环境影响，稳定性存在争议。

qCON 监测是通过脑电频谱分析，通过人工神经网络的结合和模糊逻辑系统的推导得到的单通道脑电相关指数，主要包括两类：意识指数(Quantium Consciousness Index, qCON)和伤害敏感指数(Quantium Nociceptive Index, qNOX) [32]。qCON 指数是对镇静的监测，用于监测患者由清醒到意识消失不同状态的变化，而 qNOX 是对伤害刺激的监测以预测患者对于伤害性刺激是否有体动反应[32] [33]。qCON 和 qNOX 两个指数是通过不同的脑电频率计算得出，数值范围均为 0~99。qCON 数值在 40~60 表示处于麻醉状态，qNOX 数值在 40~60 表示患者不可能对伤害性刺激有反应，0~40 表示患者对伤害性刺激有反应的可能性极低[33]。目前，关于 qCON 和 qNOX 与各种麻醉镇静药物剂量之间的相关性研究缺乏大样本的临床试验，其精确程度有待进一步探索。

熵指数是通过脑电图和前额肌电图信号的数据采集进行脑部状态监测分析得到的脑电指数，包括 2 个麻醉深度评估参数：用于评估镇静深度的状态熵(数值范围：0~100)；用于间接评估伤害性刺激或反应的反应熵(数值范围：0~91) [34] [35]。除了以上监测，临床中还有诸如 Neurosense 脑功能监测器、脑电混合统计特征实时评估、人工神经网络分析技术等脑电图衍生麻醉深度监测方法[36]-[38]。

3. 自主神经系统监测麻醉深度

全身麻醉主要作用于中枢神经系统包括皮质和皮质下结构，而脑电信号主要反映大脑皮质的功能状态和变化，对自主神经状况的评估可反映皮质下结构的活动性，麻醉深度与自主神经系统之间的关系密切，通过监测自主神经系统的反应可以有效地评估麻醉的状态和患者的生理状况，进而为麻醉深度监测提供更加全面的信息[5]。自主神经系统的功能调节可以通过多种生理指标进行评估，包括心率变异性(Heart Rate Variability, HRV)、呼吸性窦性心律不齐(Respiratory Sinus Arrhythmia, RSA)、高频瞳孔测量、皮肤电导、体温描记等，这些指标可以反映自主神经系统的平衡和紧张性，从而反应麻醉深度和生理状况[5] [39] [40]。

HRV 是指连续心搏间期的瞬时微小涨落，反映了自主神经系统对心脏节律的调节，代表自主神经系统的活动和平衡及其对内部和外部刺激的反应能力，已成为反映自主神经活动性的预测因子及无创指标，HRV 功率谱分析方法可用于评估麻醉深度和伤害性刺激的影响[41] [42]。低频功率(Low Frequency Power, LF)受心脏交感神经和迷走神经的共同影响，高频功率(High Frequency Power, HF)反映心脏迷走神经的活性，LF/HF 可定量评估交感神经和迷走神经张力的均衡性，即交感神经和迷走神经何者占优势[43]。麻醉过程中 HRV 频域指标可量化伤害性刺激引起的自主神经活动性变化，其频段成分在麻醉诱导期和手术刺激过程中发生相应变化[44]。

HRV 功率谱分析可判断丙泊酚麻醉深度，既往研究发现，丙泊酚以 BIS 依赖的方式降低 HF，表明丙泊酚降低心脏副交感神经张力取决于麻醉深度，并推断 HF 与麻醉深度相关[44]。而既往一项验证手术过程中 HRV、Narcotrend 指数和七氟烷的最小肺泡浓度之间一致性水平的研究发现，LF 和 LF/HF 与 Narcotrend 指数呈显著正相关，LF 和 LF/HF 与七氟烷的最小肺泡浓度呈负相关，HRV 反映了用于监测催眠深度的 Narcotrend 指数的趋势以及七氟烷对自主神经系统的抑制[45]。另外，HRV 非线性动力学指标近似熵、复杂度在麻醉期间发生明显的变化，可能会成为麻醉深度监测的重要指标[44]。

RSA 是指与呼吸同步的心率变异性，在吸气时心电图上的 R-R 间期缩短，在呼气时延长，是反映自主神经系统活动的指标之一，反应了迷走神经对心率的调控，与呼吸作用相关，心迷走神经活动在吸气时减弱而在呼气时增强[46] [47]。呼吸性窦性心律不齐通常反应了迷走神经对心率的调控，可以提供关于麻醉深度的信息。基于自主神经系统监测麻醉深度这种独特方法，利用与伤害性刺激相关的交感神经反应及其外部生理表现，如高频瞳孔测量可评估与交感神经刺激相关的瞳孔扩张，皮肤电导可评估出汗，在临床中具有使用价值[48] [49]。

4. 伤害性刺激监测与麻醉深度

全身麻醉需要充分的镇痛，理想的麻醉深度监测技术应具备对由手术刺激所引起的应激反应变化高度敏感的特性。因此，在脑电图、脑电图衍生参数以及自主神经系统监测麻醉深度的基础上，更全面的麻醉深度监测范围应包含伤害性刺激监测。伤害性刺激监测既可以反应全身麻醉中的镇痛水平，也可以一定程度上反应伤害性刺激带来的自主神经系统变化。虽然与 pEEG 的发展相比，伤害性刺激监测仍然处于发展阶段且未得到充分利用，但其在减少围手术期阿片类药物使用方面优于基本的临床生命体征监测。目前临床上常用的伤害性刺激监测包括镇痛伤害指数(Analgesia Nociception Index, ANI)、瞳孔测量法等。

ANI 通过分析伤害性刺激对呼吸性窦性心律的影响从而监测伤害性刺激强度，ANI 的取值范围为 0~100，数值越大，表示副交感神经张力越高，即患者的应激水平越低，其伤害性感受可能越小，表明麻醉程度越深[50]。ANI 监测是预测术中和术后疼痛有价值的衡量标准，它减少了术中阿片类药物的使用，并在围术期辅助疼痛管理[51]。瞳孔测量法测量瞳孔直径及其对伤害性刺激的反应变化，从而研究自主神

经的交感神经活动[49] [52]。全身麻醉时，随着麻醉加深双侧瞳孔会同时变小，瞳孔对光反射迟钝或消失，而在麻醉苏醒阶段，麻醉药物的逐步代谢，麻醉变浅，瞳孔会逐步恢复到正常状态。

除上述指标外，反应伤害性刺激的指标还有手术体积描计指数、伤害水平指数等。伤害性刺激反应指数能反应镇痛水平，需要在脑电监测与自主神经系统监测共同参与下提高更全面具体的麻醉深度判定[53] [54]。

5. 麻醉深度监测未来展望

目前的麻醉深度监测直接测量有限数量的全身麻醉剂对大脑的浓度依赖性影响，并间接测量全身麻醉期间的意识状态以及评估手术期间患者的应激水平(伤害感受组分)。随着技术的进步，未来麻醉管理将更加个性化，根据患者的具体需求和状态调整麻醉深度。开发更精细的监测技术，如基于深度学习的算法，以提高监测的准确性和可靠性。人工智能与麻醉深度监测的结合已成为必然趋势，未来，麻醉深度监测技术预计能够实现精确调控麻醉程度的目标，从而减少因麻醉引发的并发症，并加速患者的康复进程。

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