·综述·

可穿戴设备生态瞬时评估肠鸣音的研究进展及展望

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摘 要: 肠鸣音是反映胃肠动力状态的重要声学生理信号,在术后肠麻痹、肠梗阻、炎症性肠病等疾病评估中具有重要临床价值。传统人工听诊主观性强、可重复性低,难以实现连续客观监测。随着微电子与信号处理技术发展,可穿戴设备使肠鸣音的长期、动态、无创采集成为可能。同时,生态瞬时评估(EMA)因其能在日常生活中实时、重复采集个体行为与生理数据的特点,为突破肠鸣音监测的"瞬时性"瓶颈、实现"情境化"理解提供了新颖的方法学框架。本文系统综述可穿戴设备在肠鸣音监测中的发展历程,从固定式采集、专用便携式采集到可穿戴长期无感监测这3个阶段梳理技术演进脉络,总结肠鸣音监测在肠易激综合征、炎性肠病等多元场景中的应用价值。在此基础上首次引入EMA的理论框架,探讨其在肠鸣音监测领域的潜在价值、应用场景及面临的方法学挑战。本文指出,可穿戴技术与EMA框架的结合,可为构建高生态效度、长时程、个体化的胃肠动力监测体系提供理论依据,对推动术后护理优化、慢性胃肠疾病居家管理与精准健康监测具有重要意义。未来需聚焦设备标准化、临床验证及算法可解释性等关键问题,加速该领域发展。

关键词: 肠鸣音;生态瞬时评估;可穿戴设备;胃肠动力;精准健康监测

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Bowel Sound Monitoring with Wearable Devices for Ecological Momentary Assessment: Progress and Prospect

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Abstract: Bowel sounds are important acoustic physiological signals that reflect gastrointestinal motility and have significant clinical value in the evaluation of postoperative ileus, intestinal obstruction, and inflammatory bowel diseases. Conventional auscultation is highly subjective and often irreproducible, making continuous and objective monitoring difficult. With advances in microelectronics and signal processing technologies, wearable devices have enabled long-term, dynamic, and noninvasive acquisition of bowel sound signals. Meanwhile, ecological momentary assessment (EMA), characterized by real-time and repeated data collection of individual behaviors and physiological states in realistic situations, provides a novel methodological framework to overcome the limitations of momentary bowel sound monitoring and to facilitate context-based interpretation. This review systematically summarizes the development of wearable bowel sound monitoring technologies, outlining three stages of the technological evolution stationary acquisition, dedicated portable systems, and wearable long-term monitoring. The clinical application value of bowel sound monitoring in multiple scenarios, including irritable bowel syndrome and inflammatory bowel diseases, is also discussed. Furthermore, the theoretical framework of EMA is introduced for the first time in the field of bowel sound monitoring, and its potential value, application scenarios, and methodological challenges are explored. The integration of wearable technology with the

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EMA framework may provide a theoretical basis for constructing an, individualized long-term gastrointestinal motility monitoring system with high ecological validity, to optimize postoperative care, improve home management of chronic gastrointestinal diseases, and advance precision health monitoring. Future efforts should focus on key issues such as equipment standardization, clinical validation, and algorithmic interpretability to accelerate progress in this field.

Key words: bowel sounds; ecological momentary assessment; wearable devices; gastrointestinal motility; precision health monitoring

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肠鸣音(bowel sounds, BS)是由胃肠道蠕动推动腔内气体、液体与食糜运动而产生,并经肠壁、腹膜传导至体表的一类特殊声学信号,是反映胃肠动力状态的重要生理表征[1]。由于其非侵入性、操作便捷及能够即时反映胃肠功能状态[2],在术后肠麻痹、机械性肠梗阻、炎症性肠病等疾病的管理中具有潜在的诊断价值[3]。但人工听诊采集肠鸣音过分依赖医师经验、听觉敏感度与情境因素[4],导致主观性强与结果可重复性差,敏感性仅达到22%~32%[5]。而微电子技术与信号处理算法的进步为肠鸣音识别与分析提供了新范式[6],实现了更连续、客观的采集,在肠鸣音片段检测、分类任务中准确率甚至超过90%[7]。生态瞬时评估(ecological momentary assessment, EMA)被定义为对个体的行为、体验、情绪等实施重复采样的数据收集方法[8-9],其目的是以更为灵敏且具有弹性的方式在自然环境中进行动态测量,记录多模态数据并与情境同步整合[10]。本文围绕"可穿戴肠鸣音监测与EMA框架融合"这一核心问题,从技术发展与应用现状入手,进而分析EMA的适配机制与实施路径,探讨方法学挑战与未来方向,为构建高生态效度、长时程的胃肠动力监测体系提供理论依据。

1 肠鸣音采集技术智能化、轻量化

1.1 发展历程与理论基础

围绕信号采集的客观性、连续性与抗干扰性目标,可穿戴肠鸣音采集技术的发展历程,按其设备形态与使用范围可分为3个阶段:固定式采集阶段、专用便携式采集阶段与可穿戴式长期监测阶段。固定式采集阶段的核心是声学信号的传导、放大与记录,目标是在临床环境中获取比传统听诊更客观、可记录的短时信号。这一阶段典型设备如Littmann®CORE、Thinklabs One等商用数字听诊器[11],虽具备高保真声电转换技术,但需要通过手持操作且在不同腹部点轮流放置进行数据的采集,使其在实现舒适、长期、多通道同步连续监测方面仍存在局限[12]。专用便携式采集阶段设备形态向小型化、贴片化转变,支持受试者短时自由活动下的连续记录。例如,Zhao等[13]开发的可穿戴肠鸣音监测系统,采用贴片式传感器,使用蓝牙传输数据,且支持连续监测,并能同时监测多个自由活动状态下的被试者。Kutsumi等[14]则利用智能手机内置麦克风作为采集端,体现了采集工具向通用便携设备拓展的趋势。然而,此阶段设备仍需通过胶带等外物明显附着于体表,且部分设备仍依赖有线连接或外接记录仪,在续航、佩戴舒适性、完全无感化与无线集成方面仍面临挑战。可穿戴式长期监测阶段通过材料和技术的更新,实现了穿戴无感化与监测长期化[15]。其理论基础深入至柔性界面的声阻抗匹配、运动伪影的动态抑制以及基于长期信号的生理节律分析。Baronetto等[16]开发的智能T恤,将8个数字MEMS麦克风嵌入织物,通过服装本身固定传感器,可持续监测6 h以上。此阶段设备本身已成为穿着物或近乎无感的皮肤附着物,解决了长期佩戴的舒适性问题,为在自然生理状态下研究肠鸣音动力学、并实现监测数据对临床管理的直接指导奠定了基础。

1.2 肠鸣音监测设备特征

肠鸣音监测设备的技术发展经历了从传统电子化采集向可穿戴、智能化方向的演进。不同设备在传感器技术、可穿戴性及适用场景上各有侧重,详见表1[11, 13, 16-18]。

2 肠鸣音监测临床应用场景多元

肠鸣音的特征变化与多种消化系统疾病的病理生理过程密切相关。例如,肠易激综合征患者的

表1 肠鸣音检测设备特点汇总

Table 1 Summary of characteristics of bowel sound detection devices

Device name	Sensor technology	Wearable	Key features	Advantages	Limitations
Littmann® CORE Digital Stethoscope[11]	Dual-sided stainless steel chest piece with tunable technology; digital accessory supports Bluetooth connection	No (hand-held)	High acoustic performance; uses smartphone as interface; fixed software filters for heart and lung sounds	Reliable signal quality; high familiarity among clinicians	Heavy (232 g), bulky, high cost; unable to perform multi-channel synchronous monitoring; supports only short-term, operator-dependent manual auscultation
Thinklabs One Digital Stethoscope[11]	Patented electromagnetic diaphragm technology; detects capacitance changes between diaphragm and rear electrode plate	No (hand-held)	High sensitivity; switchable multiple filters; lightweight (50 g)	High sensitivity; flexible digital control	Highly sensitive to air gaps between sensor and skin, leading to significant performance degradation; unsuitable for long-term continuous monitoring
Wearable Bowel Sound Monitoring System (Patch-type Sensor)[13]	Patch-type sensor integrating a digital microphone and low-power microcontroller unit	Yes (patch)	Supports Bluetooth data transmission; real-time monitoring and alerting; up to 24 h of continuous operation	Enables long-term, wireless monitoring; allows limited patient mobility; supports dynamic trend analysis	Prolonged wear may cause discomfort; motion artifacts require further processing
Dedicated Contact Microphone (with Portable Recorder)[17]	Low-resonant-frequency piezoelectric sensor placed inside a custom 3D-printed stethoscope bell; acous-to-electric isolation design	Yes (patch)	High recording resolution and excellent data fidelity; primarily used for nighttime sleep monitoring	Extremely high signal fidelity; effectively captures weak bowel sounds; nighttime acquisition avoids daytime noise and dietary interference	Not capable of wireless real-time transmission; requires wearing a recording device; primarily designed for static sleep scenarios
GastroDigitalShirt (Smart T-shirt)[16]	Array of eight digital MEMS microphones embedded in elastic fabric	Yes (integrated into garment)	Sensors secured by the garment itself; supports continuous monitoring for approximately 6 h	Comfortable and unobtrusive to wear; supports synchronous monitoring at multiple anatomical sites	Fit of the garment directly affects signal quality; high system integration complexity and cost; difficult to wash and maintain
YM-TYJL-01 Continuous Bowel Sound Recorder[18]	Acquisition patch used with a Bluetooth receiver	Yes (patch)	Supports Bluetooth data transmission; wirelessly transmits data to terminal for analysis; supports multi-day continuous monitoring	It enables long-term continuous monitoring in real-world clinical settings, and the data obtained can be directly used to guide clinical management	These recommendations require further validation

肠鸣音频率(bowel sounds rate，BSR)显著高于健康人群，且肠鸣音间隔时间(bowel sounds interval，BSI))缩短，基于BSR和BSI构建的诊断模型灵敏度达78.4%，特异度达73.3%[19]。肠鸣音的监测与分析对于炎性肠病的鉴别诊断也有较高的临床价值，同时还能够帮助辨别炎性肠病是否处于活动期，准确率高达85%~91%[20]。Mao等[21]的综述指出，自动肠鸣音分析在早产儿胃肠道急症(如坏死性小肠结肠炎NEC)的早期预警中具有潜力，可能提供比传统方法更早的诊断线索。在加速康复外科理念下，准确评估术后胃肠功能恢复情况是决定何时开始安全肠内营养的关键。术后肠麻痹是腹部手术后的常见并发症，肠鸣音监测可为肠功能恢复评估提供客观依据。李嘉宇等[22]研究采用YM-TYJL-01肠鸣音记录仪对结直肠癌术后患者进行连续监测，发现肠鸣音在肛门排气前呈现特征性变化，可动态指导术后进食时机和量的临床决策，促进了患者的快速康复。可穿戴肠鸣音设备的小型化和智能化使其在家庭环境中实现长期健康监测成为可能。Zou等[23]研究提出基于半监督生成对抗网络的排便预警算法，通过智能手机采集肠鸣音数据，实现对老年失能患者排便意图的识别，准确率达94.4%。展现了可穿戴设备在家庭环境中实现主动健康管理、减轻护理负担的应用前景。有望支持居家条件下对慢性便秘、IBS等患者的肠鸣音规律的追踪。

3 生态瞬时评估在肠鸣音监测中的应用路径与价值

3.1 EMA的范式特征及其与肠鸣音监测的适配性

EMA是在自然环境中对个体当前或近期状态与行为进行实时、重复采样的研究方法集合[24]，其核心特征体现为生态性、瞬时性与重复性，旨在通过高频动态测量捕捉日常生活中的生理与行为变化，避免回溯性报告的回忆偏差[25-26]。肠鸣音作为一种高度情境依赖的生理声学信号，与自主神经张力、胃肠激素分泌及肠-脑轴活动等内在调控通路的瞬时状态紧密关联[27]，其发生频率与模式受到进食、身体活动、情绪状态、睡眠节律等多种因素的实时影响，呈现出显著的动态波动特征[28-29]。传统听诊依赖于单次、短时、医护主导的采集模式，不仅主观性强，更因脱离真实生活场景而难以反映胃肠动力的自然变化轨迹。EMA所强调的“自然场景+重复采样”范式正好能够弥补上述缺陷：一方面，通过连续、实时的数据采集，EMA可以系统捕捉肠鸣音随日常活动、饮食周期而变化的动态过程；另一方面，同步采集饮食、活动、情绪、睡眠等情境数据，为建立“情境刺激-生理响应”的时间序列关联提供了分析基础，从而将肠鸣音监测从静态信号记录拓展为动态机制探索。

EMA已广泛用于临床心理学、健康心理学及行为医学等诸多领域[30-31]，基于其强大的评估能力，相关研究由描述性向干预科学扩展。在声学相关领域，EMA目前主要聚焦于听觉功能评估、听力辅助设备效果监测及声学环境感知等主题，针对正常听力人群、听力障碍者及助听器使用者等群体[32-34]。丹麦学者Mansour等[35]系统总结EMA在听力学研究中的应用范式，包括采用智能手机应用或专用设备推送问卷，调查内容涵盖聆听场景类型、助听器满意度、残余听力障碍等，解决了传统回顾性问卷的记忆偏差问题。Andersson等[36]对15名正常听力成年人开展2周的EMA监测，采集主观聆听体验的同时利用助听器采集环境声压级与信噪比、用腕带设备采集心率数据，探索自然环境下主观聆听体验的影响相关因素。Schinkel-Bielefeld等[37]则基于EMA收集助听器使用者言语交流场景下的听力数据，为事件导向的听力EMA提供了新范式。以上研究上述研究虽来自听力学领域，但均体现了EMA“自然场景+实时采样+多维度数据整合”的核心优势，对于肠鸣音监测而言尚缺乏类似的直接实证研究，借鉴该范式意味着不仅采集声音信号，还需同步记录饮食内容、活动强度、情绪压力等情境变量，从而在时间序列上建立肠鸣音变化与生活事件之间的关联，为胃肠功能的生态化解读奠定基础。

3.2 EMA在肠鸣音监测中的实施路径与核心价值

在肠鸣音监测中实施EMA框架，其核心落地路径涵盖数据采集与数据整合两个层面。在数据采集层，需选用支持长期、连续、非侵入监测的可穿戴设备[18]，例如嵌入多通道MEMS麦克风的智能T恤或续航能力达数天的贴片式记录仪(如YM-TYJL-01)[38-39]。这些设备可在日常生活状态下持续采集肠鸣音信号，同时通过配套移动应用或内嵌传感器同步记录受试者自主报告的饮食日志、活动

类型、主观胃肠症状(如腹痛、腹胀)以及由设备自动捕捉的运动数据。在数据整合层,需将肠鸣音事件与上述情境数据在统一时间轴上实现精准对齐与关联,构建包含声学特征、行为标签与主观体验的多维度时序数据集。这一整合过程为肠鸣音监测带来2方面核心价值:一是突破传统评估的瞬时性局限,能够连续捕捉胃肠动力在昼夜周期、餐前餐后的动态演变,显著提升数据的生态效度与临床代表性;二是实现从信号记录到情境化解读的跨越,推动胃肠功能评估从描述性分析转向机制性探索。人工智能算法在该过程中扮演重要支撑角色[40],能够对EMA收集的高频、多维数据进行自动化处理[41],包括肠鸣音事件的识别分割、噪声滤除以及声学特征与情境变量之间的关联挖掘,为后续建模与解释提供技术基础[42]。

以腹泻型肠易激综合征患者为例,可构建如下EMA实施方案:选择18~65岁确诊患者于日常生活中连续监测7 d,采用YM-TYJL-01连续肠鸣音记录仪(续航≥48 h),将采集贴片粘贴于右下腹(髂前上棘与脐连线中外1/3处),实现无线连续采集。采样策略采用“连续被动采集+事件触发报告”混合模式:设备24 h不间断采集肠鸣音,获取BSR、BSI等核心参数;同时通过智能手机应用,依据延迟窗口原则,在餐前、餐后30 min、排便后、腹痛发作时由患者主动触发记录,同步记录饮食内容(拍照辅助)、腹痛VAS评分及排便性状。情境变量包括自动记录的体动数据(用于标记运动伪影)与主动报告的饮食、症状、睡眠信息。主要输出指标除BSR、BSI外,增设餐后BSR增量、腹痛前BSI缩短率等情境关联指标。为减少个体差异,在数据采集前使用标准声源对所用设备进行一致性校准,并在分析时将受试者BMI、腹壁皮下脂肪厚度及设备编号作为协变量纳入统计模型,以评估其对肠鸣音特征的影响。 而在依从性评价方面,将有效佩戴时长、事件触发报告完成率、有效数据占比等作为评价指标,还可在研究结束后补充评估用户负担。将连续肠鸣音采集与事件触发式自报告相结合,利用AI算法如目标监测算法对连续声学流进行实时或离线分析,自动识别肠鸣音的发生时刻与起止边界,将原始信号分割为独立的声学事件单元,为后续特征提取提供基本单位;利用AI的图像/信号处理优势(如U-Net或自编码器架构),结合加速度计同步采集的体动数据,自动识别并抑制运动伪影、环境噪声及腹壁肌肉干扰;同时建立信号质量评分机制(如信噪比、伪影概率),筛选出满足分析标准的有效肠鸣音片段;通过多模态融合网络(如注意力机制或Transformer模型),将肠鸣音的声学特征(如BSR、BSI、频谱能量)与饮食日志、体动数据、症状报告等情境变量在统一时间轴上进行精准对齐与关联建模,挖掘“事件-信号”之间的延迟响应模式与非线性关系。

3.3 EMA框架落地的技术支撑与现存挑战

EMA应用于肠鸣音监测,既离不开现有可穿戴设备与人工智能算法的技术支撑,也面临着若干方法学与实施层面的挑战。在设备适配性方面,当前可用的肠鸣音监测设备中,传感器与织物一体化设计,支持多解剖位点同步采集,适用于探索不同肠段活动的空间协调性;而贴片式记录仪则因体积小、续航长,更适合长期、高频的日常监测场景。同时,原始肠鸣音信号本身仍具有复杂性,包括频谱特性不稳定、事件边界模糊、个体差异显著等,因此对分析算法提出更高要求。近年来人工智能技术在肠鸣音事件识别中展现出明显优势。在典型任务中,深度学习模型整体优于传统基于特征工程的方法。德国学者基于Efficient-U-Net(EffUNet)架构的定位模型,能够在不同噪声条件下实现以0.73的回忆率和0.72的精度监测肠鸣音[43]。基于智能手机采集的研究显示,CNN模型分析肠鸣音的准确率提升至88.9%[44]。此外,ResNet-LSTM的融合结构在肠鸣音频率分类中表现突出,准确率达92.7%,Matthew相关系数达0.885,明显超过单一模型[45]。这些算法显著提升了从“大数据量、高维度”的EMA原始数据中提取有效信息的效率与准确性。

然而,EMA在肠鸣音监测中的落地仍存在一系列亟待解决的方法学挑战[46-47]:首先是如何确定最优采样频率以平衡数据丰富性与用户依从性[48],有研究表明佩戴加速度计等额外设备可能增加额外负担[49],但并未显著降低EMA应答率,提示通过可穿戴设备的被动采集(如自动记录体动、饮食时间戳)可有效替代部分主动报告,减少用户负荷;情境数据记录的标准化问题,包括饮食描述的量化、活动强度的客观标定等[33];多源异构数据的时序对齐、缺失值处理以及跨模态融合建模仍缺乏成熟方案,EMA研究中的缺失数据普遍存在,需在分析前制定明确的缺失数据处理计划,有研究表明卡尔曼

滤波在多数缺失条件下能有效恢复模型参数，而多重插补方法的参数估计效果相对不理想[50]；同时长期连续监测涉及个人隐私与数据安全[51]，需在技术设计与伦理规范层面建立完善的保障机制。这些挑战的解决是推动EMA从方法学框架走向临床实用化的关键。

4　总结与展望

综上所述，可穿戴设备与人工智能技术为肠鸣音监测提供了从主观听诊走向客观、连续与生态化评估的技术基础，而EMA方法学则为捕捉胃肠功能的动态波动提供了新的理论框架与实践路径。二者的结合提升了成功构建高时间分辨率、情境敏感、长期可持续的胃肠动力监测体系的可能性，有望未来提升术后胃肠功能恢复评估的准确性，并推动慢性胃肠疾病管理模式的升级。为推动该领域从可行性探索向临床转化，未来研究可围绕以下方面展开：针对可穿戴肠鸣音监测与EMA数据采集，建立统一的方法学标准；建立公开、标准化的肠鸣音多模态数据库，以支持算法验证、设备比较研究及模型的外部泛化能力评估；未来研究还应提升AI模型的可解释性（如注意力机制、特征可视化等），推动肠鸣音监测模块与医院信息系统或可穿戴平台的无缝集成，形成从数据采集到临床干预的闭环管理。

本综述虽梳理了可穿戴肠鸣音监测技术、临床应用价值以及EMA的潜在应用路径，但仍存在部分局限性。由于当前直接采用EMA框架用于肠鸣音监测的研究数量有限，部分论述需借鉴听力监测、皮肤电导等其他生理学监测领域的证据，可能影响外推性。其次，基于EMA肠鸣音监测的最佳采样频率、负荷控制、用户依从性及伦理问题等方面尚未形成共识，影响其在未来临床应用中的推广。此外，现有设备和算法多处于原型或实验性阶段[52]，缺乏大规模临床验证，因此其在真实世界情境下的可行性仍需进一步研究。

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