Journal of Pain Research

Dovepress

Open Access Full Text Article

REVIEW

Beyond the Pain Management Clinic: The Role of AI-Integrated Remote Patient Monitoring in Chronic Disease Management – A Narrative Review

Prachi M Patel[1], Maja Green[2], Jennifer Tram[3], Eugene Wang[4], Melissa Zhu Murphy[5], Alaa Abd-Elsayed[6], Krishnan Chakravarthy[2]

[1]Houston Methodist Willowbrook Hospital, Houston, TX, USA; [2]NXTSTIM, San Diego, CA, USA; [3]UCLA David Geffen School of Medicine/VA Greater Los Angeles Healthcare System, Los Angeles, CA, 90095, USA; [4]Timothy Groth MD PC, Smithtown, NY, 11787, USA; [5]North Texas Orthopedics and Spine Center, Grapevine, TX, 76051, USA; [6]University of Wisconsin School of Medicine and Public Health, Madison, WI, USA

Correspondence: Maja Green, Chief Scientific Officer, NXTSTIM Inc., Department of Pain Medicine, 5362 SweetwaterTrails, San Diego, CA, 92132, USA, Email mgreen@nxtstim.com

---

Abstract: Remote Patient Monitoring (RPM) stands as a pivotal advancement in patient-centered care, offering substantial improvements in the diagnosis, management, and outcomes of chronic conditions. Through the utilization of advanced digital technologies, RPM facilitates the real-time collection and transmission of critical health data, enabling clinicians to make prompt, informed decisions that enhance patient safety and care, particularly within home environments. This narrative review synthesizes evidence from peer-reviewed studies to evaluate the transformative role of RPM, particularly its integration with Artificial Intelligence (AI), in managing chronic conditions such as heart failure, diabetes, and chronic pain. By highlighting advancements in disease-specific RPM applications, the review underscores RPM's versatility and its ability to empower patients through education, shared decision-making, and adherence to therapeutic regimens. The COVID-19 pandemic further emphasized the importance of RPM in ensuring healthcare continuity during systemic disruptions. The integration of AI with RPM has refined these capabilities, enabling personalized, real-time data collection and analysis. While chronic pain management serves as a focal area, the review also examines AI-enhanced RPM applications in cardiology and diabetes. AI-driven systems, such as the NXTSTIM EcoAI™, are highlighted for their potential to revolutionize treatment approaches through continuous monitoring, timely interventions, and improved patient outcomes. This progression from basic wearable devices to sophisticated, AI-driven systems underscores RPM's ability to redefine healthcare delivery, reduce system burdens, and enhance quality of life across multiple chronic conditions. Looking forward, AI-integrated RPM is expected to further refine disease management strategies by offering more personalized and effective treatments. The broader implications, including its applicability to cardiology, diabetes, and pain management, showcase RPM's capacity to deliver automated, data-driven care, thereby reducing healthcare burdens while enhancing patient outcomes and quality of life.

Keywords: remote patient monitoring, RPM, chronic disease management, AI integrated care

---

Introduction

The evolution of mobile and remote health technologies has marked a significant shift in the landscape of healthcare, particularly in the management of chronic diseases. RPM has emerged as a crucial innovation, leveraging digital technology to bridge the gap between patients and clinicians. By enabling the continuous collection, monitoring, and transmission of health data from patients to healthcare providers, RPM represents a paradigm shift from reactive to proactive healthcare. This shift significantly enhances the potential for early intervention, personalized treatment strategies, and ultimately, improved patient outcomes.[1–3] Clinically, RPM has demonstrated remarkable efficacy across various chronic conditions, including heart failure, diabetes, and chronic pain. For example, in heart failure, real-time

Received: 7 September 2024
Accepted: 8 December 2024
Published: 11 December 2024

monitoring of physiological parameters such as cardiac biomarkers, blood pressure, and heart rate variability allows for timely adjustments in therapy that can avert severe complications.[4–6] Similarly, in diabetes management, continuous glucose monitoring (CGM) provides immediate insights into glucose levels, enabling better glycemic control and reducing the risk of complications. These real-time data collection methods uncover patterns and trends that traditional, episodic assessments often miss, allowing for more precise and tailored interventions that address the dynamic nature of chronic diseases.[3,7,8] These real-time data collection methods uncover patterns and trends that traditional, episodic assessments often miss, allowing for more precise and tailored interventions that are responsive to the dynamic nature of chronic diseases.[6] The integration of AI with RPM technology further enhances its capabilities, enabling the analysis of vast amounts of data generated by RPM devices. AI algorithms can detect subtle patterns and correlations that might escape human analysis, leading to more accurate risk stratification, earlier detection of complications, and optimization of treatment plans tailored to the individual patient's profile. For example, AI-driven systems like the NXTSTIM EcoAI™ have shown potential in chronic pain management by continuously monitoring biomarkers and physiological signals, detecting changes in pain pathways, or identifying the development of tolerance to neuromodulation therapies. These insights allow for timely adjustments to treatment regimens, ensuring sustained therapeutic efficacy and reducing the risk of pain exacerbation.[3,6,9] Despite these advancements, several knowledge gaps remain. While RPM has shown significant promise, there is limited understanding of its full potential when integrated with AI in emerging areas like chronic pain management. Additionally, current literature has focused primarily on cardiology and diabetes, with fewer studies exploring the scalability and adaptability of RPM in diverse patient populations or across varying healthcare settings. Questions also persist regarding the long-term efficacy of AI-driven RPM systems, particularly in optimizing therapeutic interventions and reducing healthcare burdens. This review aims to address these gaps by analyzing the transformative role of RPM in cardiology, diabetes, and chronic pain management, showcasing its potential to enhance patient outcomes and healthcare system efficiency.

The evolution of RPM technology from basic wearable devices to sophisticated implanted systems represents a significant leap forward in patient care. These advancements facilitate continuous, non-invasive monitoring of a wide range of physiological parameters, providing clinicians with a comprehensive view of the patient's health status. This shift to continuous monitoring contrasts sharply with traditional, intermittent, office-based assessments, which often fail to capture the dynamic progression of chronic diseases. Moreover, the use of AI within RPM systems extends beyond reactive care, offering predictive analytics that can foresee complications such as device malfunctions or therapy resistance before they become clinically apparent. This proactive approach enables preemptive clinical interventions, reducing the likelihood of adverse events and optimizing patient outcomes (Figure 1).[10,11] For vulnerable populations, such as the elderly, disabled, or chronically ill patients who may have difficulty visiting healthcare facilities, RPM provides a critical solution to ensure continuous and accessible care. These individuals often face barriers to regular healthcare access due to mobility limitations, comorbidities, or inadequate support, making remote monitoring a practical and effective approach. RPM can facilitate continuous treatment adjustments and personalized care from home, minimizing the need for frequent clinic visits and enhancing overall patient comfort and satisfaction. Additionally, RPM has the potential to significantly alleviate the burden on healthcare systems by enabling the management of chronic conditions within the patient's home. This not only enhances patient satisfaction but also optimizes healthcare resource allocation, allowing resources to be directed toward more acute cases.[10] The scalability of RPM solutions further allows them to be deployed across various settings, from rural areas with limited access to healthcare facilities to urban centers where healthcare systems are often overburdened. This broad implementation ensures that all patients, regardless of geographic or socioeconomic status, can benefit from high-quality, continuous care. As RPM technology continues to evolve, its integration into routine clinical practice will likely become increasingly widespread. The development of more advanced sensors, improved data analytics, and seamless integration with electronic health records will further enhance the utility of RPM in delivering high-quality, patient-centered care.[9,12,13] The combination of RPM and AI offers transformative potential that goes beyond individual patient outcomes to impact broader healthcare delivery by reducing costs and improving system-wide efficiency. This integrated approach not only empowers clinicians to make proactive, data-driven decisions but also streamlines the management of chronic pain and other conditions, supporting better long-term health outcomes for vulnerable patient groups. The sustained progression of RPM and AI technologies will ensure

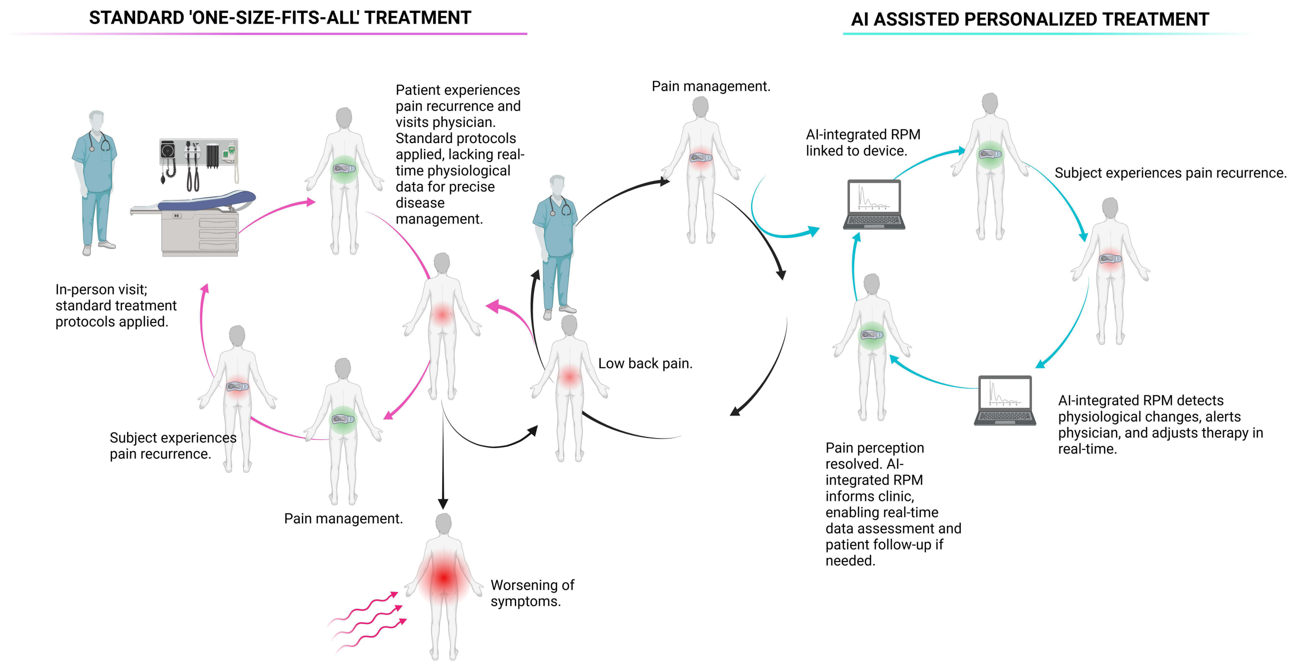

Figure 1 Comparison of Standard "One-Size-Fits-All" Treatment versus AI-Assisted Personalized Treatment in Chronic Disease Management.

Notes: The left panel illustrates the traditional approach, where patients receive standardized treatment regimens based on fixed protocols. This method often requires frequent clinic visits for therapy adjustments, increasing both cost and time burdens. As the disease progresses, the static treatment plan may lose efficacy, leading to the need for higher doses or additional medications, which can increase the risk of adverse effects. In contrast, the right panel depicts AI-assisted personalized treatment, where continuous real-time monitoring through AI-integrated RPM enables dynamic therapy adjustments without the need for frequent clinic visits. This personalized approach optimizes treatment efficacy by continuously adapting to the individual's disease progression, reducing the risk of adverse effects, and ultimately enhancing patient outcomes.

their role in healthcare continues to expand, emphasizing personalized care, reducing hospital visits, and enhancing overall patient quality of life.[9,10,14,15]

This narrative review examines the clinical impact of RPM, focusing on its applications in cardiology, diabetes, and chronic pain management. By analyzing the insights gained from these implementations and considering RPM's future potential, the article underscores its transformative role in addressing the identified knowledge gaps, enhancing patient care, and optimizing healthcare resources.

The Transformative Role of RPM in Managing Cardiac Implantable Electronic Devices (CIEDs)

One of the most significant applications of RPM is in the field of cardiology, particularly in the management of CIEDs, such as pacemakers and implantable cardioverter-defibrillators (ICDs). These devices are critical in the management of patients with cardiac arrhythmias, providing life-saving interventions by regulating heart rhythms or delivering shocks to prevent sudden cardiac death. The clinical management of these devices, however, presents unique challenges, particularly in the post-implantation phase where regular monitoring is essential to ensure device functionality and patient safety.[16,17] Traditionally, the follow-up care for patients with CIEDs has been conducted through scheduled in-office visits involving device interrogation, battery checks, and assessments of the device's therapeutic effectiveness.[18–21] However, the frequency and scheduling of these follow-ups have not been standardized, leading to variability in patient management. This traditional model of care places a significant burden on both patients and healthcare systems. Patients are often required to travel long distances for frequent check-ups, which can be particularly challenging for those with limited mobility or those residing in rural areas. Moreover, the reliance on in-office visits for device monitoring consumes valuable healthcare resources, contributing to increased costs and inefficiencies within the healthcare system.[22] Before the advancement of RPM, there was a notable gap in patient care between these scheduled follow-up visits. Patients were essentially unsupervised during the intervals between visits, creating a period of vulnerability where potential device malfunctions or arrhythmia episodes could go undetected. This lack of continuous surveillance posed significant risks, as issues with CIEDs could lead to severe adverse events, including worsening arrhythmias, device failure, or even sudden cardiac death.[23–25]

RPM has revolutionized the management of CIEDs by enabling continuous, real-time monitoring of device function and patient status. Through RPM, data from the implanted devices are automatically transmitted to healthcare providers at regular intervals, or when specific thresholds are breached, such as abnormal heart rhythms or low battery levels. This constant surveillance allows for the early detection of potential issues, facilitating timely interventions that can prevent complications and improve patient outcomes.[17,26,27]

Additionally, the ability of RPM to provide continuous monitoring also addresses the challenges associated with the etiology and pathology of cardiac arrhythmias as they often exhibit an unpredictable and episodic nature, with events that may not occur during scheduled follow-up visits.[26,28–30] The pathophysiology of these conditions, which can involve complex interactions between electrical, structural, and autonomic factors within the heart, necessitates ongoing surveillance for effective management. RPM allows for the capture of real-time data on these episodic events, providing insights into the patient's arrhythmic burden and the efficacy of the CIED in mitigating these events. Furthermore, the integration of RPM with AI and advanced data analytics holds the potential to further refine the management of cardiac arrhythmias.[31–33] AI algorithms can analyze the vast amounts of data generated by RPM systems to detect subtle patterns or trends that may indicate a worsening condition, even before clinical symptoms manifest. This predictive capability can guide preemptive interventions, potentially preventing adverse outcomes and further optimizing patient care.[34] By providing continuous, real-time monitoring and enabling early interventions, RPM not only enhances the safety and efficacy of CIEDs but also improves the overall quality of care for patients with cardiac arrhythmias. As RPM technology continues to evolve, it is poised to play an increasingly central role in the management of cardiovascular diseases, offering a more patient-centered, efficient, and effective approach to care.

Clinical Efficacy Through RPM in Cardiac Care: Insights from Key Clinical Trials

RPM has emerged as a crucial innovation in the management of patients with implantable cardiac devices, with significant evidence supporting its efficacy and potential to optimize healthcare resource utilization. Multiple clinical trials have demonstrated RPM's ability to improve patient outcomes by enabling continuous monitoring, early detection of complications, and timely intervention, thereby reducing the need for in-person visits and hospital admissions.[5,34]

The (Lumos-T Safely Reduces Routine Office Device Follow-Up) TRUST trial was a pivotal study that emphasized the value of RPM in managing patients with implantable ICDs. In this trial, 1339 patients were randomized in a 2:1 ratio to receive either remote home monitoring with automatic daily surveillance (HM) or conventional in-office follow-up. The primary outcome measure was the frequency of in-hospital device evaluations, and the study found a significant 45% reduction in these evaluations for the HM group without any increase in morbidity. Notably, 85.8% of patients in the HM group were successfully monitored remotely, underscoring RPM as a safe and effective alternative to traditional in-office follow-up. The outcomes of the TRUST trial demonstrated that RPM could maintain patient safety while significantly reducing the burden on healthcare resources.[35]

Another key study, the CONNECT (Clinical Evaluation of Remote Notification to Reduce Time to Clinical Decision) trial, involved 1997 patients across 136 sites. This multicenter, prospective, randomized trial aimed to assess the impact of RPM on the time from a cardiac event to clinical intervention. The primary outcome was the median time to intervention, which was dramatically reduced from 22 days in the conventional follow-up group to just 2.6 days in the RPM group. Additionally, secondary outcome measures included the length of hospital stays, with the RPM group experiencing a shorter average stay of 3.3 days compared to 4.0 days in the conventional group. These results highlighted RPM's ability to enhance the efficiency of care delivery, ensuring that patients receive timely interventions while reducing hospital resource consumption.[36]

The IN-TIME (Implant-based multiparameter telemonitoring of patients with heart failure) trial further validated the role of RPM in heart failure management. This randomized, multicenter, international study enrolled 664 patients with

New York Heart Association (NYHA) class II–III symptoms, an ejection fraction of less than 35%, and recent cardiac resynchronization therapy defibrillator (CRT-D) or dual-chamber ICD implantation. The primary outcome was a composite clinical score that included all-cause mortality, heart failure-related hospitalizations, and changes in NYHA class. After one year, the trial demonstrated that 18.9% of patients in the RPM group experienced worsened outcomes compared to 27.2% in the standard care group. The findings underscored the importance of RPM in improving clinical outcomes for heart failure patients by facilitating early intervention and reducing the risk of disease progression.[37]

Additionally, a recent pivotal study investigated the use of a wireless implantable hemodynamic monitoring system for the daily measurement of pulmonary artery pressures in heart failure patients. The primary outcome was the reduction in heart failure-related hospitalizations, with the RPM group showing significantly fewer hospitalizations over six months compared to those receiving standard care alone. This study further validated the clinical efficacy of RPM in managing chronic cardiac conditions, demonstrating its ability to reduce the frequency of acute decompensations and hospital admissions.[38] RPM has also shown promise in managing other chronic conditions, such as hypertension.[39] A study conducted in a primary care setting with 118 patients found that RPM led to better blood pressure control in pilot practices compared to matched controls over a six-month period. The primary outcome was the achievement of target blood pressure levels, with RPM demonstrating superior control. However, the study also noted challenges in both provider and patient adoption of RPM, highlighting the need for dedicated clinical personnel to effectively review and act on the collected data.[40]

Collectively, these studies underscore the critical role of RPM in modern healthcare. By enabling continuous monitoring and timely intervention, RPM not only improves patient outcomes but also optimizes healthcare resource utilization. The ability to reduce hospital admissions, shorten hospital stays, and maintain patient safety with fewer in-person visits makes RPM a transformative tool in the management of chronic diseases. However, to fully realize its potential, challenges related to adoption, data management, and clinical integration must be addressed, ensuring that RPM becomes a standard component of patient care.

Advancements in Continuous Glucose Monitoring (CGM): Transforming Diabetes Management and Clinical Outcomes

The emergence of CGM and flash glucose monitoring technologies has revolutionized diabetes management by enabling real-time insights into interstitial glucose levels, a critical factor in understanding the disease's molecular underpinnings and progression. These technologies, while facing challenges in precision, such as in metrics like mean absolute relative difference and consensus error grid analysis, offer substantial clinical benefits. CGM enhances glycemic control, reduces the incidence of hypoglycemia, and improves overall quality of life, particularly in patient populations requiring intensive glucose management, such as elderly patients with type 2 diabetes, post-surgical, post-transplantation patients, pregnant women, and individuals experiencing glucose fluctuations due to hemodialysis or cardiovascular events.[41–45]

CGM technology allows for continuous, real-time monitoring of glucose, providing critical data that directly impacts the management of hyperglycemia and its associated molecular mechanisms, including insulin resistance and beta-cell dysfunction. By diminishing the reliance on frequent fingerstick tests, CGM offers a comprehensive view of glucose dynamics, which is particularly beneficial for patients with complex insulin regimens or those prone to significant glucose variability.[46] The potential for CGM in hospital settings, especially highlighted during the COVID-19 pandemic, demonstrated its utility in reducing patient-provider contact, thereby conserving personal protective equipment (PPE) and minimizing infection risk. However, this also emphasized the need for deliberate integration of CGM into clinical workflows, given the complexity of managing glucose levels in acutely ill patients.[27,47]

Effective integration of CGM in hospitals requires careful selection of devices based on their functionality and understanding potential interferences that could affect molecular data accuracy. It also necessitates identifying appropriate patient populations, ensuring device compatibility with existing medical infrastructure, establishing rigorous sterilization protocols, and embedding CGM into routine clinical practices. A thorough evaluation of the safety, efficacy, and cost-effectiveness of CGM is critical for its broader adoption in hospital care, particularly in managing the molecular and physiological complexities of diabetes.[48] Clinically, CGM has shown promise in various settings, demonstrating its ability to improve outcomes and reduce complications by providing continuous feedback on glucose levels, which is crucial for managing the molecular pathways involved in diabetes, such as the regulation of hepatic glucose production and peripheral glucose uptake. In elderly patients with type 2 diabetes, CGM has enhanced glycemic control, decreased hypoglycemic events, and provided valuable data on glucose trends, particularly in those with cognitive impairment, where glucose fluctuations can exacerbate neurodegenerative processes. In emergency care, CGM can play a pivotal role in managing hyperglycemia associated with increased mortality in acute conditions such as myocardial infarction and stroke, by providing real-time data that can be critical in preventing glucose-induced endothelial damage and oxidative stress.[48,49] In addition to this it may have a potential in reducing the risk of long-term complications like retinopathy and nephropathy, For post-transplant patients, who often experience significant hyperglycemia due to immunosuppressive therapy, CGM provides continuous glucose data, enabling better management of glucose homeostasis, potentially improving transplant outcomes by reducing the risk of infection and graft rejection associated with poor glycemic control.[50] In patients with chronic kidney disease and type 2 diabetes, CGM is instrumental in understanding daily glucose patterns, optimizing insulin therapy, and preventing hypoglycemic episodes during hemodialysis, a time when the balance of glucose metabolism is particularly fragile due to altered renal clearance and insulin sensitivity. CGM-derived metrics, such as the glucose management indicator (GMI), offer more accurate reflections of glycemic control compared to HbA1c, especially in these populations where standard measures may be confounded by the disease's molecular pathophysiology.[48] During pregnancy, CGM is vital for women with pre-existing diabetes or gestational diabetes mellitus (GDM), as it helps maintain tight glycemic control, thereby reducing the risk of adverse outcomes for both mother and child, such as macrosomia and preeclampsia, which are linked to maternal hyperglycemia's impact on fetal development. The continuous data provided by CGM allows for real-time adjustments in therapy, which is crucial for managing the rapidly changing insulin sensitivity during pregnancy.[48] While CGM represents a significant advancement in diabetes management, challenges remain, including sensor accuracy, data interpretation, and integration into clinical practice. The implementation of CGM in hospital settings demands careful planning to ensure its safety, effectiveness, and cost-efficiency, particularly in managing the complex molecular aspects of diabetes. Additionally, addressing the social and emotional aspects of CGM use, such as potential stigma and the psychological impact of wearing a sensor, is essential. Education and support for both patients and healthcare providers are critical to maximizing the benefits of CGM data and improving diabetes care outcomes.[51]

These advancements in CGM technology offer substantial opportunities for enhancing diabetes management across diverse clinical scenarios. As the technology continues to evolve, its role in improving glycemic control, reducing complications, and elevating patient care standards will become increasingly central to the management of diabetes in both outpatient and inpatient settings, with significant implications for patient outcomes and healthcare resource utilization.

Clinical Integration of RPM: Opportunities and Challenges

RPM has demonstrated significant clinical value, particularly when the data collected leads to tangible improvements in patient care and outcomes. In the management of chronic conditions like heart failure and diabetes, RPM has shown its potential to enhance longitudinal disease management while simultaneously increasing patient engagement. The ability for patients, caregivers, and healthcare providers to access real-time data facilitates a collaborative approach to care, where personalized treatment goals can be set, monitored, and adjusted dynamically. This real-time feedback not only empowers patients to take an active role in their health but also provides flexibility, reducing the frequency and burden of in-office clinic visits.[9,52] However, the integration of RPM into clinical practice is not without its challenges. Ensuring the security and privacy of the data collected and transmitted is paramount, as any breaches could compromise patient trust and violate legal standards. The sheer volume of data generated by RPM systems requires timely interpretation and response, necessitating trained staff and well-established clinical workflows. Failure to address alerts appropriately or delays in response can lead to significant medico-legal risks, particularly in cases where timely intervention is critical. Additionally, when RPM is used for screening, there is a risk of triggering unnecessary and costly diagnostic workups, potentially leading to patient anxiety and increased healthcare costs without clear clinical benefit.[53–56]

In heart failure management, RPM has highlighted key considerations in data collection and analysis. Selecting the right patients for RPM is crucial, as those at higher risk for decompensation may derive the most benefit from continuous monitoring. The choice of devices and the method of data transmission are also critical factors influencing both provider and patient adherence. Passive data transmission and the use of minimally invasive sensors are more likely to be accepted by patients and result in better adherence to monitoring protocols. Furthermore, setting appropriate clinical alert thresholds is essential to reduce false positives and ensure that only clinically actionable data prompts provider intervention. This optimization helps avoid alert fatigue among healthcare providers and ensures that critical information is acted upon swiftly.[4,56] The 2023 heart Rhythm Society consensus statement provides valuable insights into the successful implementation of RPM, particularly in the field of cardiac electrophysiology, where it has become the standard of care for patients with CIEDs. Among the key takeaways, the statement emphasizes the importance of establishing robust clinical care pathways and ensuring adequate staffing to manage the increased workload associated with RPM. Staff members must be adequately trained and given sufficient time to respond to patient data transmissions effectively.[57,58] High-priority alerts should be programmed to help triage critical and time-sensitive information, enabling healthcare teams to focus on the most urgent clinical needs. The consensus statement also recommends standardized clinical management protocols and suggests that partnerships with device manufacturers and third-party resources can be instrumental in managing the high volume of data generated by RPM systems.[59] It is important to consider, while RPM presents significant opportunities to enhance patient care, its successful integration into clinical practice requires careful planning, appropriate patient selection, and the establishment of comprehensive clinical protocols. Addressing these challenges will be key to maximizing the benefits of RPM and ensuring that it contributes meaningfully to improved patient outcomes and more efficient healthcare delivery.[58,60]

AI Integration in RPM: Enhancing Precision Medicine in Chronic Disease Management

The integration of AI within RPM systems marks a significant advancement in clinical care, particularly in managing chronic diseases. AI, particularly through machine learning algorithms, is designed to process and analyze vast amounts of data generated by continuous monitoring devices. These algorithms are capable of identifying complex patterns and correlations within the data that are often imperceptible through traditional statistical methods. This capability is critical in RPM, where large datasets from wearable and implantable devices must be rapidly interpreted to inform clinical decision-making.[61]

AI design in RPM systems typically involves the use of deep neural networks (DNNs), a subset of ML that mimics the structure of the human brain with layers of interconnected nodes. These networks are trained using vast datasets to recognize specific patterns, such as those associated with disease exacerbations or therapeutic responses. Once trained, DNNs can analyze new data in real-time, continuously refining their predictive models based on incoming information. This allows RPM systems to dynamically adjust treatment regimens in response to physiological changes, optimizing patient outcomes while minimizing the risk of adverse effects.[3] For example, in the management of atrial fibrillation, DNNs have been employed to enhance the sensitivity and specificity of implantable loop recorders. By filtering out noise and reducing the incidence of false positives, these AI-driven systems ensure that only clinically significant arrhythmic events trigger alerts, thereby improving the efficiency of clinical workflows and ensuring timely interventions. The use of AI in this context also extends to the predictive maintenance of cardiac devices, where algorithms can forecast device malfunctions before they occur, preventing potential complications.[62–64]

In diabetes management, AI-enhanced RPM systems analyze CGM data alongside other biomarkers such as insulin levels, heart rate variability, and inflammatory markers. By integrating these data points, AI can model the patient's metabolic state in real-time, predicting hyperglycemic or hypoglycemic episodes before they manifest clinically.[65] This enables preemptive adjustments to insulin therapy, thereby maintaining tighter glycemic control and reducing the risk of long-term complications.[66–68]

The physical principles underlying AI in RPM involve complex signal processing techniques, such as Fourier transforms and wavelet analysis, which are used to decompose physiological signals into their constituent frequencies.

These techniques allow AI systems to detect subtle changes in signal patterns that may indicate early disease progression or treatment response. For example, in hemodynamic monitoring, AI algorithms can analyze pressure waveforms to detect early signs of heart failure decompensation, allowing for timely therapeutic interventions.[69,70]

Despite these advancements, the integration of AI in RPM poses challenges that must be addressed to maximize its clinical utility. Ensuring the robustness and generalizability of AI algorithms is critical, as biases in training data can lead to inaccurate predictions. Furthermore, the interpretability of AI outputs remains a significant concern; clinicians must be able to understand and trust the rationale behind AI-driven recommendations to integrate them effectively into patient care. Additionally, stringent data security protocols are essential to protect patient information and comply with regulatory requirements.[71]

By leveraging advanced machine learning techniques, these systems can deliver precise, personalized care, ultimately improving clinical outcomes and reducing the burden on healthcare systems. As AI technology continues to advance, its role in RPM will likely expand, paving the way for new approaches to disease management that are both data-driven and patient-centered.

Advanced Pain Management: The Integral Role of AI Integrated RPM

Pain is regulated through complex pathways involving peripheral and central nervous systems, where nociceptive signaling, neurotransmitter release and neuroinflammatory responses play critical roles.[72] AI-enhanced RPM systems can continuously monitor biomarkers and physiological signals, such as cytokine levels, neurotransmitter fluctuations and nerve conduction velocities, offering real-time insights into these pain pathways. By analyzing this data, AI can detect subtle changes in pain signaling or the emergence of new pain pathways, which may indicate disease progression or treatment resistance. For example, AI can monitor central sensitization, a process where the central nervous system becomes hyper-responsive to stimuli, often leading to chronic pain.[15,73] In chronic pain management, RPM systems provide continuous data on a patient's physiological status, including vital signs, activity levels, and specific pain-related biomarkers. This data is crucial for assessing the effectiveness of ongoing treatments and identifying the need for adjustments. When integrated with AI, RPM systems can analyze this data to detect early signs of treatment failure, such as increased inflammation or altered pain signaling, which might indicate that the disease is progressing or that the patient is developing tolerance to current therapies.[73]

Uniting Innovation and Compassion: Advancing Pain Management with AI-Enhanced RPM and Neuromodulation Therapies

SCS, peripheral nerve stimulation (PNS), transcutaneous electrical nerve stimulation (TENS), and electromyographic stimulation (EMS) are sophisticated neuromodulation therapies designed to modulate neural activity within the central and peripheral nervous systems, directly targeting nociceptive pathways that mediate pain perception. These therapies are particularly effective in managing chronic pain conditions, including neuropathic pain, complex regional pain syndrome (CRPS), and failed back surgery syndrome (FBSS), by influencing the transmission and processing of pain signals at the molecular level.[74–77]

Nociception, the process by which pain is detected and transmitted, involves the activation of nociceptors, specialized sensory neurons that respond to potentially harmful stimuli. Upon activation, these neurons release neurotransmitters such as glutamate and substance P, which bind to receptors on dorsal horn neurons in the spinal cord. This interaction leads to the depolarization of these neurons and the propagation of pain signals to higher brain centers, where they are perceived as pain. Central sensitization, a key feature in chronic pain, occurs when these pathways become hyper-responsive due to persistent stimulation, leading to an amplification of pain signals.[72,78,79] SCS and PNS therapies modulate these nociceptive pathways by delivering electrical impulses that inhibit the transmission of pain signals. These impulses are believed to activate large-diameter Aβ fibers, which in turn inhibit the activity of smaller, pain-transmitting C fibers through mechanisms such as presynaptic inhibition and the activation of inhibitory interneurons. This modulation reduces the perception of pain by altering the balance of excitatory and inhibitory neurotransmitter release in the dorsal horn of the spinal cord.[80,81] AI-enhanced RPM systems add a significant dimension to the management of patients receiving SCS and PNS therapies by continuously tracking patient-reported outcomes and device-specific data, such as lead impedance, battery status, and stimulation parameters. By integrating advanced AI algorithms, these systems can analyze real-time data to detect molecular and physiological changes that may indicate shifts in pain pathways or therapy efficacy. For example, changes in biomarkers associated with neuroinflammation, such as cytokine levels, alterations in neurotransmitter profiles, or fluctuations in nerve conduction velocities, can be identified. These biomarkers often signal the development of tolerance to neuromodulation therapy, characterized by neuroplastic changes that reduce its effectiveness over time.

When these early signs of therapy resistance or suboptimal efficacy are detected, AI can recommend adjustments to neuromodulation parameters, such as altering pulse width, frequency, or amplitude, to restore therapeutic benefits. By correlating these adjustments with patient-reported pain scores and physiological indicators like heart rate variability (HRV), AI systems can personalize therapy to ensure long-term success. Furthermore, the ability to track trends in neurochemical mediators, such as serotonin and norepinephrine levels, enhances the understanding of how therapies influence descending pain inhibition pathways, leading to more targeted and effective treatments.[73,82–87] Recent advancements in the use of TENS have further highlighted the potential of AI-enhanced RPM systems in optimizing stimulation parameters. TENS efficacy has been shown to depend heavily on stimulation amplitude, which influences the recruitment of sensory fibers and activation of endogenous pain modulatory pathways. AI systems can analyze real-time feedback from biomarkers such as HRV, skin conductance, and muscle oxygenation to guide amplitude adjustments dynamically. These adjustments are crucial in conditions like central sensitization, where higher stimulation amplitudes may be needed to counteract hyperalgesia and allodynia effectively.[88–93]

Recent advancements in the use of TENS have further highlighted the potential of AI-enhanced RPM systems in optimizing stimulation parameters. TENS efficacy has been shown to depend heavily on stimulation amplitude, which influences the recruitment of sensory fibers and activation of endogenous pain modulatory pathways. AI systems can analyze real-time feedback from biomarkers such as HRV, skin conductance, and muscle oxygenation to guide amplitude adjustments dynamically. These adjustments are crucial in conditions like central sensitization, where higher stimulation amplitudes may be needed to counteract hyperalgesia and allodynia effectively.[94,95] The ability of AI-enhanced RPM systems to predict and preempt complications such as lead migration, battery depletion, or therapy resistance represents a significant advancement in chronic pain management. By continuously monitoring device performance and physiological responses, these systems enable timely interventions that prevent disruptions in therapy and ensure sustained patient comfort. This predictive capability fosters a proactive approach to pain management, reducing the need for frequent clinician interventions and enhancing patient satisfaction. In acute pain settings, such as postoperative pain management, AI-enhanced patient-controlled analgesia (AI-PCA) systems have demonstrated notable benefits, including reduced incidence of severe pain and shorter hospital stays. These systems leverage AI to assess pain-related biomarkers and patient inputs in real time, enabling precise dose adjustments that minimize adverse effects while optimizing pain relief. This integration of AI and RPM exemplifies how personalized pain management can be achieved through continuous monitoring and adaptive interventions.[96,97]

Recent study have explored novel biomarkers that can be used to monitor and optimize TENS therapy in clinical settings.[98] Among these, HRV has emerged as a promising indicator of autonomic nervous system regulation during TENS treatment. Higher TENS amplitudes have been associated with greater improvements in HRV indices, reflecting a shift toward enhanced parasympathetic activity and reduced sympathetic drive. This autonomic modulation is closely linked to improvements in pain scores and patient-reported outcomes, suggesting that HRV could serve as a holistic biomarker to guide TENS amplitude adjustments in real-time.[99] Other biomarkers, such as skin conductance and muscle oxygenation levels, are also being investigated for their potential to provide objective insights into the physiological effects of TENS at varying amplitudes. By correlating TENS amplitude with biomarkers such as HRV and neurochemical changes, clinicians can develop personalized pain management strategies that maximize analgesic outcomes. As research continues to advance, the identification of novel biomarkers and the integration of AI-based RPM systems could revolutionize the way TENS therapy is delivered, allowing for continuous optimization of stimulation parameters based on real-time physiological feedback. This approach not only enhances the precision of TENS therapy but also paves the way for more effective and individualized pain management intervention. These findings underscore the amplitude of TENS stimulation as a crucial factor in influencing the recruitment of neural pathways and activating endogenous pain modulatory mechanisms. By correlating TENS amplitude with biomarkers such as HRV and neurochemical changes, clinicians can develop personalized pain management strategies that maximize analgesic outcomes. As research continues to advance, the identification of novel biomarkers and the integration of AI-based RPM(RPM) systems could revolutionize the delivery of TENS therapy, allowing for continuous optimization of stimulation parameters based on real-time physiological feedback. This approach not only enhances the precision of TENS therapy but also paves the way for more effective and individualized pain management interventions.[100,101]

In parallel, AI-enhanced RPM systems offer a transformative opportunity for managing neuromodulation therapies beyond TENS, such as SCS and PNS. These systems provide real-time adaptability to evolving pain conditions, ensuring the therapy remains effective without frequent clinician intervention. In some cases, these adjustments can be automatically implemented by the system, ensuring that the therapy remains effective without requiring frequent clinician intervention. This real-time adaptability is crucial in managing chronic pain, where the underlying pathophysiology can evolve, necessitating continuous optimization of treatment.[88] Moreover, AI-enhanced RPM systems offer predictive analytics capabilities, which are essential for preempting complications such as lead migration or battery depletion. By monitoring device-specific metrics and physiological indicators, the system can forecast potential issues before they manifest clinically, allowing for timely interventions that prevent therapy interruptions and maintain patient comfort and satisfaction.[73,102] The integration of AI within RPM for SCS and PNS therapies represents a paradigm shift in the management of chronic pain. By providing a dynamic, responsive approach to neuromodulation, AI-enhanced RPM not only improves the precision and efficacy of pain management but also enhances the overall patient experience. This technology fosters a more personalized treatment plan, continually adapting to the patient's changing clinical status and ensuring that neuromodulation therapies remain effective over the long term. As AI and RPM technologies continue to advance, their role in chronic pain management will become increasingly central, offering a more sophisticated and patient-centered approach to treating complex pain conditions.[103–105]

AI's ability to detect molecular and signaling changes allows for early identification of therapy resistance. For instance, if RPM data indicates shifts in cytokine profiles or neurotransmitter levels, suggesting an inflammatory response or altered nociception, AI can flag these changes as potential signs of disease progression or treatment resistance. Clinicians can then adjust the therapeutic approach, whether through medication changes, reprogramming neuromodulation devices, or introducing adjunctive therapies.

In acute postoperative pain management, AI-enhanced patient-controlled analgesia (AI-PCA) systems have demonstrated significant benefits, including reduced incidence of moderate to severe pain and shorter hospital stays. By integrating AI with RPM, these systems continuously assess pain-related biomarkers and patient inputs, enabling real-time adjustments to analgesic dosing and ensuring effective pain management while minimizing the risk of overmedication and adverse effects.[106] The integration of AI and RPM in pain management represents a significant advancement in personalized care. AI's capacity to detect changes in signaling and biomarkers enables early identification of therapy resistance or disease progression, prompting timely adjustments to treatment plans. This approach not only improves clinical outcomes by ensuring therapies remain effective but also enhances patient quality of life by reducing the burden of chronic pain. As AI and RPM technologies continue to evolve, their role in pain management will become increasingly central to achieving optimal, patient-centered care.

Discussion

The integration of RPM and AI represents a transformative evolution in chronic disease management, transitioning care from traditional, episodic models to continuous, proactive, and highly personalized approaches. This paradigm shift has far-reaching implications for improving patient outcomes and optimizing healthcare system efficiency, particularly in the management of complex chronic conditions such as heart failure, diabetes, and chronic pain.

RPM's clinical value lies in its ability to continuously monitor physiological parameters and biomarkers, providing real-time data to support timely therapeutic adjustments. In cardiology, for example, RPM has been shown to reduce hospital admissions, shorten hospital stays, and improve overall outcomes. Notable studies, such as the TRUST and CONNECT trials, demonstrate that RPM can enhance the efficiency of care delivery in patients with cardiac implantable electronic devices (CIEDs) by reducing the time from event detection to clinical intervention while alleviating the burden on healthcare resources. These findings underscore RPM's potential to revolutionize chronic disease management in cardiology.

In diabetes management, CGM integrated with AI has reshaped care delivery, offering immediate insights into glucose levels. This enables better glycemic control, particularly in vulnerable populations such as elderly patients, pregnant women with gestational diabetes, and individuals with chronic kidney disease. Real-time data generated by CGM devices allow for proactive adjustments in therapy, preventing both hyperglycemic and hypoglycemic episodes. By identifying trends and patterns that traditional monitoring often overlooks, RPM enhances therapeutic precision and patient safety. The integration of AI-enhanced RPM systems in chronic pain management is one of the most promising developments in neuromodulation therapies. Systems like the NXTSTIM EcoAI™ exemplify cutting-edge technology by enabling the continuous monitoring of patient-reported outcomes, physiological signals, and device-specific data. AI's ability to detect subtle changes in pain pathways or therapy tolerance enables timely adjustments to treatment regimens, ensuring sustained therapeutic efficacy and reducing the risk of chronic pain exacerbation. This dynamic adaptability is particularly relevant in managing conditions such as lower back pain, where the system's predominant use underscores its efficacy in addressing one of the most prevalent causes of chronic pain. The versatility of the NXTSTIM EcoAI™ device in managing pain across other sites, such as the knee, upper back, and buttock, further highlights its broad therapeutic potential.

However, the integration of RPM and AI into routine clinical practice presents challenges. Data security, managing the sheer volume of data generated, and addressing potential biases in AI algorithms are critical issues. Clinicians must trust and understand AI-generated recommendations to make informed decisions, emphasizing the need for transparency and interpretability in AI models. Moreover, the successful adoption of these technologies requires collaboration among clinicians, technologists, and healthcare administrators. Standardized protocols, robust clinical workflows, and adequate training are essential to fully harness their potential. Patient education and engagement are equally crucial to optimize adherence to RPM protocols and maximize their benefits.

The adoption of RPM and AI represents a paradigm shift in chronic disease management, particularly for chronic pain. By enabling continuous, real-time monitoring and facilitating personalized, dynamic adjustments to therapy, these technologies enhance patient outcomes while reducing the strain on healthcare resources. Future research should investigate the long-term outcomes of AI-enhanced RPM, including its impact on functional recovery and quality of life, to better understand its role in managing chronic diseases comprehensively.

Conclusion

The integration of RPM and AI is transforming the management of chronic diseases, offering a more precise, personalized, and proactive approach to patient care. By enabling continuous, real-time monitoring of physiological parameters and biomarkers, RPM facilitates timely interventions and tailored treatment strategies, significantly improving patient outcomes and optimizing healthcare resource utilization. AI amplifies these capabilities by analyzing vast datasets, detecting subtle patterns, and predicting complications, thereby enabling proactive and efficient care delivery. In chronic pain management, AI-enhanced RPM systems, such as the NXTSTIM EcoAI™, exemplify the future of neuromodulation therapies. These systems adapt to evolving clinical conditions in real-time, ensuring sustained therapeutic efficacy while enhancing patient quality of life. The ability to preempt complications and adjust therapies dynamically reduces the need for frequent in-person visits, offering convenience and improving long-term outcomes.

As RPM and AI technologies continue to advance, their integration into routine clinical practice is poised to revolutionize chronic disease management. This shift toward a more sophisticated, patient-centered, and efficient healthcare model has the potential to redefine care delivery for complex chronic conditions, paving the way for a new era in healthcare. Further research into their long-term impacts will solidify their role in improving functional recovery, patient satisfaction, and overall quality of life.

Disclosure

Maja Green and Krishnan Chakravarthy are employees of NXTSTIM Inc. Melissa Murphy reports speaking, research, advisory board from Medtronic, advisory board for Pacira, stock holder, advisory board from Nervonik, consultant for Relievent Inc, outside the submitted work.

References

1. Vegesna A, Tran M, Angelaccio M, Arcona S. Remote patient monitoring via non-invasive digital technologies: a systematic review. *Telemed J E Health*. 2017;23(1):3–17. doi:10.1089/tmj.2016.0051
2. Farias FAC, Dagostini CM, Bicca YA, Falavigna VF, Falavigna A. Remote patient monitoring: a systematic review. *Telemed J E Health*. 2020;26(5):576–583. doi:10.1089/tmj.2019.0066
3. Deo RC. Machine learning in medicine. *Circulation*. 2015;132(20):1920–1930. doi:10.1161/CIRCULATIONAHA.115.001593
4. Bhatia A, Maddox TM. Remote patient monitoring in heart failure: factors for clinical efficacy. *Int J Heart Fail*. 2021;3(1):31–50. doi:10.36628/ijhf.2020.0023
5. Nakamura N, Koga T, Iseki H. A meta-analysis of remote patient monitoring for chronic heart failure patients. *J Telemed Telecare*. 2014;20(1):11–17. doi:10.1177/1357633X13517352
6. Ross EL, Jamison RN, Nicholls L, Perry BM, Nolen KD. Clinical Integration of a Smartphone App for Patients With Chronic Pain: retrospective Analysis of Predictors of Benefits and Patient Engagement Between Clinic Visits. *J Med Internet Res*. 2020;22(4):e16939. doi:10.2196/16939
7. Alboksmaty A, Beaney T, Elkin S, et al. Effectiveness and safety of pulse oximetry in remote patient monitoring of patients with COVID-19: a systematic review. *Lancet Digit Health*. 2022;4(4):e279–e89. doi:10.1016/S2589-7500(21)00276-4
8. Su D, Michaud TL, Estabrooks P, et al. Diabetes management through remote patient monitoring: the importance of patient activation and engagement with the technology. *Telemed J E Health*. 2019;25(10):952–959. doi:10.1089/tmj.2018.0205
9. Tan SY, Sumner J, Wang Y, Wenjun Yip A. A systematic review of the impacts of remote patient monitoring (RPM) interventions on safety, adherence, quality-of-life and cost-related outcomes. *NPJ Digit Med*. 2024;7(1):192. doi:10.1038/s41746-024-01182-w
10. Chen W, Khurshid S, Singer DE, et al. Cost-effectiveness of screening for atrial fibrillation using wearable devices. *JAMA Health Forum*. 2022;3(8):e222419. doi:10.1001/jamahealthforum.2022.2419
11. Bhatia A, Ewald G, Maddox T. The novel data collection and analytics tools for remote patient monitoring in heart Failure (Nov-RPM-HF) trial: protocol for a single-center prospective trial. *JMIR Res Protoc*. 2022;11(6):e32873. doi:10.2196/32873
12. Kazzi B, Chino F, Kazzi B, et al. Shared burden: the association between cancer diagnosis, financial toxicity, and healthcare cost-related coping mechanisms by family members of non-elderly patients in the USA. *Support Care Cancer*. 2022;30(11):8905–8917. doi:10.1007/s00520-022-07234-9
13. Deitelzweig SB, Lovelace B, Christoph M, Lingohr-Smith M, Lin J, Fermann GJ. Evaluation of the incremental healthcare economic burden of patients with atrial fibrillation treated with direct-acting oral anticoagulants and hospitalized for major bleeds in the USA. *Adv Ther*. 2020;37(9):3942–3953. doi:10.1007/s12325-020-01440-9
14. Lappegard KT, Moe F. Remote monitoring of CIEDs-for both safety, economy and convenience? *Int J Environ Res Public Health*. 2021;19(1):312. doi:10.3390/ijerph19010312
15. Peterson S. Telerehabilitation booster sessions and remote patient monitoring in the management of chronic low back pain: a case series. *Physiother Theory Pract*. 2018;34(5):393–402. doi:10.1080/09593985.2017.1401190
16. Peacock WF, Clark CL. *Short Stay Management of Atrial Fibrillation*. Imprint: Humana: Cham: Springer International Publishing; 2016.
17. Haghjoo M, Kamali F, Fazelifar AF. *Radiographic Atlas of Cardiac Implantable Electronic Devices*. First edition. ed. Philadelphia, PA: Elsevier; 2022:xi,82pagesp.
18. Vogiatzis I, Sdogkos E, Galitsianos I, Koutsambasopoulos K, Stalidou Z. Clinical features, follow-up, and reprogramming of patients with pacemaker in a secondary care center. *Hippokratia*. 2018;22(2):75–79.
19. Zanotto G, Cassinadri E, Visentin E, et al. From in-clinic to fully remote follow-up model for pacemaker patients: a four-year experience. *Int J Cardiol*. 2018;258:151–153. doi:10.1016/j.ijcard.2018.01.122
20. Parsova KE, Hayiroglu MI, Pay L, Cinier G, Gurkan K. Long-term follow-up of patients with drug-related atrioventricular block without a need of permanent pacemaker during index hospitalization. *Egypt Heart J*. 2022;74(1):56. doi:10.1186/s43044-022-00297-3
21. Gramegna L, Tomasi C, Gasparini G, et al. In-hospital follow-up of implantable cardioverter defibrillator and pacemaker carriers: patients' inconvenience and points of view. A four-hospital Italian survey. *Europace*. 2012;14(3):345–350. doi:10.1093/europace/eur334
22. Dickman SL, Himmelstein DU, Woolhandler S. Inequality and the health-care system in the USA. *Lancet*. 2017;389(10077):1431–1441. doi:10.1016/S0140-6736(17)30398-7
23. Morin DP. Pacemaker failure as a cause of sudden death. *Virchows Arch*. 2018;472(2):293. doi:10.1007/s00428-017-2244-6
24. Li YD, Hong YF, Ma JH, et al. Effects of pacemaker implantation on sudden cardiac death rate and quality of life in atrial fibrillation patients with ventricular pauses. *Angiology*. 2022;73(2):99–103. doi:10.1177/00033197211028022
25. Arai Y, Shibata A, Kazama K, Makino H, Saitoh Y. A new pacemaker for monitoring asystole and prevention of Adams-Stokes syndrome and sudden cardiac death. *Pacing Clin Electrophysiol*. 1984;7(6 Pt 1):973–978. doi:10.1111/j.1540-8159.1984.tb05647.x
26. Valverde Andre I, Gonzalez Vasserot M, Gonzalez Chana B, et al. Early remote monitoring of pacemaker devices and benefits of this paradigm shift. The FAST REMOTE study. *Rev Esp Cardiol (Engl Ed)*. 2023;76(5):379–381. doi:10.1016/j.rec.2022.09.015
27. Melissano D, Gualtieri MR, Greco A, Muscella A, Marzo A, Perrone C. Creation of pacemaker remote monitoring networks between hospital and pharmacies during Covid-19 outbreak. *Indian Pacing Electrophysiol J*. 2023;23(4):116–119. doi:10.1016/j.ipej.2023.05.003
28. Freeman JV, Saxon L. Remote monitoring and outcomes in pacemaker and defibrillator patients: big data saving lives? *J Am Coll Cardiol*. 2015;65(24):2611–2613. doi:10.1016/j.jacc.2015.04.031

29. Kawakami H, Saito M, Fujisawa T, et al. A cost-effectiveness analysis of remote monitoring after pacemaker implantation for bradycardia in Japan. *J Cardiol*. 2023;82(5):388–397. doi:10.1016/j.jjcc.2023.06.003
30. Garcia-Fernandez FJ, Osca Asensi J, Romero R, et al. Safety and efficiency of a common and simplified protocol for pacemaker and defibrillator surveillance based on remote monitoring only: a long-term randomized trial (RM-ALONE). *Eur Heart J*. 2019;40(23):1837–1846. doi:10.1093/eurheartj/ehz067
31. Sciarra L, Romano S, Paparella G, Scara A. Editorial: pharmacological therapy in patients with arrhythmias. *Front Pharmacol*. 2024;15:1465539. doi:10.3389/fphar.2024.1465539
32. Milzi A, Thomsen TA, Landi A, et al. Diagnostic accuracy of quantitative flow ratio in patients with arrhythmias. *EuroIntervention*. 2024;20(16):1039–1041. doi:10.4244/EIJ-D-24-00144
33. El Mathari S, Tomsic A, Kharbanda RK, et al. Characterization of atrial arrhythmias following mitral valve repair: incidence and risk factors. *J Cardiovasc Electrophysiol*. 2024;35(10):1972–1980. doi:10.1111/jce.16390
34. Guedon-Moreau L, Mabo P, Kacet S. Current clinical evidence for remote patient management. *Europace*. 2013;15 Suppl 1(suppl_1):i6–i10. doi:10.1093/europace/eut119
35. Varma N, Epstein AE, Irimpen A, Schweikert R, Love C. Efficacy and safety of automatic remote monitoring for implantable cardioverter-defibrillator follow-up: the Lumos-T Safely Reduces Routine Office Device Follow-up (TRUST) trial. *Circulation*. 2010;122(4):325–332. doi:10.1161/CIRCULATIONAHA.110.937409
36. Crossley GH, Boyle A, Vitense H, Chang Y, Mead RH. The CONNECT (Clinical Evaluation of Remote Notification to Reduce Time to Clinical Decision) trial: the value of wireless remote monitoring with automatic clinician alerts. *J Am Coll Cardiol*. 2011;57(10):1181–1189. doi:10.1016/j.jacc.2010.12.012
37. Hindricks G, Taborsky M, Glikson M, et al. Implant-based multiparameter telemonitoring of patients with heart failure (IN-TIME): a randomised controlled trial. *Lancet*. 2014;384(9943):583–590. doi:10.1016/S0140-6736(14)61176-4
38. Abraham WT, Adamson PB, Bourge RC, et al. Wireless pulmonary artery haemodynamic monitoring in chronic heart failure: a randomised controlled trial. *Lancet*. 2011;377(9766):658–666. doi:10.1016/S0140-6736(11)60101-3
39. Lee SG, Fisher NDL. Innovative remote management solutions for the control of hypertension. *Hypertension*. 2023;80(5):945–955. doi:10.1161/HYPERTENSIONAHA.122.19436
40. Petito LC, Anthony L, Peprah YA, et al. Remote physiologic monitoring for hypertension in primary care: a prospective pragmatic pilot study in electronic health records using propensity score matching. *JAMIA Open*. 2023;6(1):ooac111. doi:10.1093/jamiaopen/ooac111
41. Zhou Y, Sardana D, Kuroko S, et al. Comparing the glycaemic outcomes between real-time continuous glucose monitoring (rt-CGM) and intermittently scanned continuous glucose monitoring (isCGM) among adults and children with type 1 diabetes: a systematic review and meta-analysis of randomized controlled trials. *Diabet Med*. 2024;41(3):e15280. doi:10.1111/dme.15280
42. Uhl S, Choure A, Rouse B, Loblack A, Reaven P. Effectiveness of continuous glucose monitoring on metrics of glycemic control in type 2 diabetes mellitus: a systematic review and meta-analysis of randomized controlled trials. *J Clin Endocrinol Metab*. 2024;109(4):1119–1131. doi:10.1210/clinem/dgad652
43. Seidu S, Kunutsor SK, Ajjan RA, Choudhary P. Efficacy and safety of continuous glucose monitoring and intermittently scanned continuous glucose monitoring in patients with type 2 diabetes: a systematic review and meta-analysis of interventional evidence. *Diabetes Care*. 2024;47(1):169–179. doi:10.2337/dc23-1520
44. Patel PM, Thomas D, Liu Z, Aldrich-Renner S, Clemons M, Patel BV. Systematic review of disparities in continuous glucose monitoring and insulin pump utilization in the United States: key themes and evidentiary gaps. *Diabetes Obes Metab*. 2024;26(10):4293–4301. doi:10.1111/dom.15774
45. Jia Y, Long D, Yang Y, Wang Q, Wu Q, Zhang Q. Diabetic peripheral neuropathy and glycemic variability assessed by continuous glucose monitoring: a systematic review and meta-analysis. *Diabet Res Clin Pract*. 2024;213:111757. doi:10.1016/j.diabres.2024.111757
46. Ajjan RA, Cummings MH, Jennings P, Leelarathna L, Rayman G, Wilmot EG. Accuracy of flash glucose monitoring and continuous glucose monitoring technologies: implications for clinical practice. *Diab Vasc Dis Res*. 2018;15(3):175–184. doi:10.1177/1479164118756240
47. Galindo RJ, Aleppo G, Klonoff DC, et al. Implementation of continuous glucose monitoring in the hospital: emergent considerations for remote glucose monitoring during the COVID-19 pandemic. *J Diabetes Sci Technol*. 2020;14(4):822–832. doi:10.1177/1932296820932903
48. Klupa T, Czupryniak L, Dzida G, et al. Expanding the role of continuous glucose monitoring in modern diabetes care beyond type 1 disease. *Diabetes Ther*. 2023;14(8):1241–1266. doi:10.1007/s13300-023-01431-3
49. Jospe MR, Richardson KM, Saleh AA, et al. Leveraging continuous glucose monitoring as a catalyst for behaviour change: a scoping review. *Int J Behav Nutr Phys Act*. 2024;21(1):74. doi:10.1186/s12966-024-01622-6
50. Jandovitz N, George SJ, Abate M, et al. A randomized trial of continuous glucose monitoring to improve post-transplant glycemic control. *Clin Transplant*. 2023;37(12):e15139. doi:10.1111/ctr.15139
51. Philis-Tsimikas A, Diego E, Vincent L, Lohnes S, Singleton C. Are we ready for real-time continuous glucose monitoring in the hospital setting? Benefits, challenges, and practical approaches for implementation: case vignette: remote real-time continuous glucose monitoring for hospitalized care in Quincy Koala. *Curr Diab Rep*. 2024;24(10):217–226. doi:10.1007/s11892-024-01549-z
52. Wathne H, May C, Morken IM, Storm M, Husebo AML. Acceptability and usability of a nurse-assisted remote patient monitoring intervention for the post-hospital follow-up of patients with long-term illness: a qualitative study. *Int J Nurs Stud Adv*. 2024;7:100229. doi:10.1016/j.ijnsa.2024.100229
53. Secher PH, Egmose J, Hejlesen O, Hangaard S. Usability Evaluation of a Web-Based Remote Patient Monitoring Application: an Ongoing Study. *Stud Health Technol Inform*. 2024;316:125–126. doi:10.3233/SHTI240360
54. G R, M S, Mathivanan SK, Shivahare BD, Chandan RR, Shah MA. A comprehensive health assessment approach using ensemble deep learning model for remote patient monitoring with IoT. *Sci Rep*. 2024;14(1):15661. doi:10.1038/s41598-024-66427-w
55. Chu F, Stark A, Telzak A, Rikin S. Patient experience in a remote patient monitoring program for hypertension: a qualitative study. *Am J Hypertens*. 2024;37(11):861–867. doi:10.1093/ajh/hpae086
56. Brugts JJ. Remote haemodynamic monitoring and the next step: involving the patient in the self-management of heart failure. *Eur J Heart Fail*. 2024;26(8):1824–1826. doi:10.1002/ejhf.3355
57. Wilsmore B, Leitch J. Remote monitoring of medical devices in Australia. *Med J Aust*. 2017;206(2):62–63. doi:10.5694/mja16.00730

58. Van Biesen W, Decruyenaere J, Sideri K, Cockbain J, Sterckx S. Remote digital monitoring of medication intake: methodological, medical, ethical and legal reflections. *Acta Clin Belg*. 2021;76(3):209–216. doi:10.1080/17843286.2019.1708152
59. Ferrick AM, Raj SR, Deneke T, et al. 2023 hRS/EHRA/APHRS/LAHRS expert consensus statement on practical management of the remote device clinic. *Heart Rhythm*. 2023;20(9):e92–e144. doi:10.1016/j.hrthm.2023.03.1525
60. Keil A, Gaus O, Bruck R, Hahn K. Concept of a new medical data-driven health care model based on remote patient monitoring. *Annu Int Conf IEEE Eng Med Biol Soc*. 2023;2023:1–4. doi:10.1109/EMBC40787.2023.10340292
61. Zoppo G, Marrone F, Pittarello M, et al. AI technology for remote clinical assessment and monitoring. *J Wound Care*. 2020;29(12):692–706. doi:10.12968/jowc.2020.29.12.692
62. Kalscheur MM, Akbilgic O. AI-Enabled ECG for Paroxysmal Atrial Fibrillation Detection: one Step to Closer to the Finish Line. *JACC Clin Electrophysiol*. 2023;9(8 Pt 3):1783–1785. doi:10.1016/j.jacep.2023.05.023
63. Freedman B. An AI-ECG algorithm for atrial fibrillation risk: steps towards clinical implementation. *Lancet*. 2020;396(10246):236. doi:10.1016/S0140-6736(20)31063-1
64. Baqal O, Habib EA, Hasabo EA, et al. Artificial intelligence-enabled electrocardiogram (AI-ECG) does not predict atrial fibrillation following patent foramen ovale closure. *Int J Cardiol Heart Vasc*. 2024;51:101361. doi:10.1016/j.ijcha.2024.101361
65. Dubey A, Tiwari A. Artificial intelligence and remote patient monitoring in US healthcare market: a literature review. *J Mark Access Health Policy*. 2023;11(1):2205618. doi:10.1080/20016689.2023.2205618
66. Park SW, Kim G, Hwang YC, Lee WJ, Park H, Kim JH. Validation of the effectiveness of a digital integrated healthcare platform utilizing an AI-based dietary management solution and a real-time continuous glucose monitoring system for diabetes management: a randomized controlled trial. *BMC Med Inform Decis Mak*. 2020;20(1):156. doi:10.1186/s12911-020-01179-x
67. DeJournett J, Nekludov M, DeJournett L, Wallin M. Performance of a closed-loop glucose control system, comprising a continuous glucose monitoring system and an AI-based controller in swine during severe hypo- and hyperglycemic provocations. *J Clin Monit Comput*. 2021;35(2):317–325. doi:10.1007/s10877-020-00474-2
68. Anjum M, Saher R, Saeed MN. Optimizing type 2 diabetes management: AI-enhanced time series analysis of continuous glucose monitoring data for personalized dietary intervention. *PeerJ Comput Sci*. 2024;10:e1971.
69. Zhang Y, Guo Z, Wang W, He S, Lee T, Loew M. A comparison of the wavelet and short-time Fourier transforms for Doppler spectral analysis. *Med Eng Phys*. 2003;25(7):547–557. doi:10.1016/S1350-4533(03)00052-3
70. Coorevits P, Danneels L, Cambier D, et al. Correlations between short-time Fourier- and continuous wavelet transforms in the analysis of localized back and Hip muscle fatigue during isometric contractions. *J Electromyogr Kinesiol*. 2008;18(4):637–644. doi:10.1016/j.jelekin.2007.01.006
71. Mittal S, Oliveros S, Li J, Barroyer T, Henry C, Gardella C. AI filter improves positive predictive value of atrial fibrillation detection by an implantable loop recorder. *JACC Clin Electrophysiol*. 2021;7(8):965–975. doi:10.1016/j.jacep.2020.12.006
72. Basbaum AI, Bautista DM, Scherrer G, Julius D. Cellular and molecular mechanisms of pain. *Cell*. 2009;139(2):267–284. doi:10.1016/j.cell.2009.09.028
73. Zhong T, William HM, Jin MY, Abd-Elsayed A. A review of remote monitoring in neuromodulation for chronic pain management. *Curr Pain Headache Rep*. 2024. doi:10.1007/s11916-024-01302-x
74. Tran EL, Crawford LK. Revisiting PNS plasticity: how uninjured sensory afferents promote neuropathic pain. *Front Cell Neurosci*. 2020;14:612982. doi:10.3389/fncel.2020.612982
75. Naidu R, Li S, Desai MJ, Sheth S, Crosby ND, Boggs JW. 60-Day PNS treatment may improve identification of delayed responders and delayed non-responders to neurostimulation for pain relief. *J Pain Res*. 2022;15:733–743. doi:10.2147/JPR.S349101
76. Mekhail NA, Levy RM, Deer TR, et al. ECAP-controlled closed-loop versus open-loop SCS for the treatment of chronic pain: 36-month results of the EVOKE blinded randomized clinical trial. *Reg Anesth Pain Med*. 2024;49(5):346–354. doi:10.1136/rapm-2023-104751
77. Berg AP, Mekel-Bobrov N, Goldberg E, Huynh D, Jain R. Utilization of multiple spinal cord stimulation (SCS) waveforms in chronic pain patients. *Expert Rev Med Devices*. 2017;14(8):663–668. doi:10.1080/17434440.2017.1345621
78. Vallejo R, Gupta A, Cedeno DL, et al. Clinical effectiveness and mechanism of action of spinal cord stimulation for treating chronic low back and lower extremity pain: a systematic review. *Curr Pain Headache Rep*. 2020;24(11):70. doi:10.1007/s11916-020-00907-2
79. Ong Sio LC, Hom B, Garg S, Abd-Elsayed A. Mechanism of action of peripheral nerve stimulation for chronic pain: a narrative review. *Int J Mol Sci*. 2023;24(5):4540. doi:10.3390/ijms24054540
80. van den Broeke EN, Lambert J, Huang G, Mouraux A. Central sensitization of mechanical nociceptive pathways is associated with a long-lasting increase of pinprick-evoked brain potentials. *Front Hum Neurosci*. 2016;10:531. doi:10.3389/fnhum.2016.00531
81. Kendroud S, Fitzgerald LA, Murray IV, Hanna A. *Physiology, Nociceptive Pathways*. Treasure Island (FL): StatPearls; 2024.
82. Brandao M, Talih M, Holden S, Fernandes F, Graven-Nielsen T, Lucas R. Pain history and experimental pressure pain responses in adolescents: results from a population-based birth cohort. *Eur J Pain*. 2024;28(1):70–82. doi:10.1002/ejp.2159
83. Karri J, Li S, Chen YT, Stampas A, Li S. Observations of autonomic variability following central neuromodulation for chronic neuropathic pain in spinal cord injury. *Neuromodulation*. 2021;24(3):427–433. doi:10.1111/ner.12979
84. Suhalka A, da Silva Areas FZ, Meza F, et al. Dosing overground robotic gait training after spinal cord injury: a randomized clinical trial protocol. *Trials*. 2024;25(1):690. doi:10.1186/s13063-024-08503-0
85. Obaid AT, Bader MZ, Shroof BH, Hroub AA, Abukhudair HY. The effect of remote-based monitoring and education program on cancer pain management in an outpatient pain clinic. *Pain Manag Nurs*. 2022;23(6):742–751. doi:10.1016/j.pmn.2022.04.004
86. Noah B, Keller MS, Mosadeghi S, et al. Impact of remote patient monitoring on clinical outcomes: an updated meta-analysis of randomized controlled trials. *NPJ Digit Med*. 2018;1(1):20172. doi:10.1038/s41746-017-0002-4
87. Staats P, Deer TR, Hunter C, et al. Remote management of spinal cord stimulation devices for chronic pain: expert recommendations on best practices for proper utilization and future considerations. *Neuromodulation*. 2023;26(7):1295–1308. doi:10.1016/j.neurom.2023.07.003
88. Gozani SN. Remote analgesic effects of conventional transcutaneous electrical nerve stimulation: a scientific and clinical review with a focus on chronic pain. *J Pain Res*. 2019;12:3185–3201. doi:10.2147/JPR.S226600
89. Ward AR, Lucas-Toumbourou S, McCarthy B. A comparison of the analgesic efficacy of medium-frequency alternating current and TENS. *Physiotherapy*. 2009;95(4):280–288. doi:10.1016/j.physio.2009.06.005

90. Dimitrova A, Harrington A, Memmott T, Sisley J, Oken B. Acupuncture-induced changes in nociception, measured by pain-related evoked potentials: a pilot mechanistic study. *J Integr Complement Med*. 2022;28(11):862–869. doi:10.1089/jicm.2021.0369
91. Pantaleao MA, Laurino MF, Gallego NL, et al. Adjusting pulse amplitude during transcutaneous electrical nerve stimulation (TENS) application produces greater hypoalgesia. *J Pain*. 2011;12(5):581–590. doi:10.1016/j.jpain.2010.11.001
92. Chen CC, Johnson MI. An investigation into the effects of frequency-modulated transcutaneous electrical nerve stimulation (TENS) on experimentally-induced pressure pain in healthy human participants. *J Pain*. 2009;10(10):1029–1037. doi:10.1016/j.jpain.2009.03.008
93. Kulikova N, Khalilovich AM, Konchugova T, et al. Analgesic effects of high-frequency and low-frequency TENS currents in patients with distal neuropathy. *Eur J Transl Myol*. 2022;32(3). doi:10.4081/ejtm.2022.10687.
94. Telles JD, Schiavon MAG, Costa ACS, Rampazo EP, Liebano RE. Hypoalgesic Effects of Transcutaneous Electrical Nerve Stimulation Combined With Joint Manipulation: a Randomized Clinical Trial. *J Manipulative Physiol Ther*. 2021;44(3):244–254. doi:10.1016/j.jmpt.2020.09.004
95. Cowan S, McKenna J, McCrum-Gardner E, Johnson MI, Sluka KA, Walsh DM. An investigation of the hypoalgesic effects of TENS delivered by a glove electrode. *J Pain*. 2009;10(7):694–701. doi:10.1016/j.jpain.2008.12.004
96. Xing GG, Liu FY, Qu XX, Han JS, Wan Y. Long-term synaptic plasticity in the spinal dorsal horn and its modulation by electroacupuncture in rats with neuropathic pain. *Exp Neurol*. 2007;208(2):323–332. doi:10.1016/j.expneurol.2007.09.004
97. Bi Y, Wei Z, Kong Y, Hu L. Supraspinal neural mechanisms of the analgesic effect produced by transcutaneous electrical nerve stimulation. *Brain Struct Funct*. 2021;226(1):151–162. doi:10.1007/s00429-020-02173-9
98. Seenan C, Roche PA, Tan CW, Mercer T. Modification of experimental, lower limb ischemic pain with transcutaneous electrical nerve stimulation. *Clin J Pain*. 2012;28(8):693–699. doi:10.1097/AJP.0b013e318242fccb
99. Lazarou L, Kitsios A, Lazarou I, Sikaras E, Trampas A. Effects of intensity of Transcutaneous Electrical Nerve Stimulation (TENS) on pressure pain threshold and blood pressure in healthy humans: a randomized, double-blind, placebo-controlled trial. *Clin J Pain*. 2009;25(9):773–780. doi:10.1097/AJP.0b013e3181a7ece3
100. Berardi G, Dailey DL, Chimenti R, et al. Influence of Transcutaneous Electrical Nerve Stimulation (TENS) on pressure pain thresholds and conditioned pain modulation in a randomized controlled trial in women with fibromyalgia. *J Pain*. 2024;25(6):104452. doi:10.1016/j.jpain.2023.12.009
101. Yilmaz E, Karakaya E, Baydur H, Tekin I. Effect of transcutaneous electrical nerve stimulation on postoperative pain and patient satisfaction. *Pain Manag Nurs*. 2019;20(2):140–145. doi:10.1016/j.pmn.2018.06.003
102. Lu Y, Xie D, Zhang X, et al. Management of intractable pain in patients with implanted spinal cord stimulation devices during the COVID-19 pandemic using a remote and wireless programming system. *Front Neurosci*. 2020;14:594696. doi:10.3389/fnins.2020.594696
103. Harnik MA, Kesselring P, Ott A, Urman RD, Luedi MM. Complex Regional Pain Syndrome (CRPS) and the Value of Early Detection. *Curr Pain Headache Rep*. 2023;27(9):417–427. doi:10.1007/s11916-023-01124-3
104. Arcos-Holzinger M, Biebl JT, Storz C, et al. Virtual reality in managing Complex Regional Pain Syndrome (CRPS): a scoping review. *Front Neurol*. 2023;14:1069381. doi:10.3389/fneur.2023.1069381
105. Allmendinger F, Scheuren PS, De Schoenmacker I, et al. Contact-heat evoked potentials: insights into pain processing in CRPS Type I. *J Pain Res*. 2024;17:989–1003. doi:10.2147/JPR.S436645
106. Wang D, Guo Y, Yin Q, et al. Analgesia quality index improves the quality of postoperative pain management: a retrospective observational study of 14,747 patients between 2014 and 2021. *BMC Anesthesiol*. 2023;23(1):281. doi:10.1186/s12871-023-02240-8