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Advancing Cardiovascular Care: A Comprehensive Review of Portable and Continuous Monitoring Devices in Cardiovascular Radiology

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REVIEW ARTICLE

ABSTRACT

Cardiovascular radiology has witnessed significant advancements with the introduction and widespread adoption of portable and continuous monitoring devices. These technologies have revolutionized patient care by providing real-time, comprehensive cardiovascular health assessments. This narrative review explores the current landscape of portable and continuous monitoring devices in cardiovascular radiology. It examines their applications, impact on early detection of complications, influence on mortality rates, and potential side effects associated with prolonged use. By synthesizing recent research and clinical guidelines, this review aims to thoroughly understand these devices' role in modern cardiovascular care and their potential to shape future diagnostic and treatment paradigms.

Keywords: Cardiovascular Radiology, Portable Monitoring Devices, Continuous Monitoring, Early Detection, Patient Care.

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INTRODUCTION

Cardiovascular diseases remain a leading cause of morbidity and mortality worldwide, necessitating innovative approaches to diagnosis, monitoring, and treatment. Integrating portable and continuous monitoring devices into cardiovascular radiology is a promising strategy to enhance patient care and improve clinical outcomes. These devices offer the potential for real-time, non-invasive assessment of cardiovascular parameters, enabling early detection of complications and timely interventions.

Advancements in miniaturization, wireless communication, and data analytics have driven the evolution of monitoring technologies. From traditional Holter monitors to sophisticated implantable devices and wearable sensors, the field has expanded rapidly to encompass a wide array of tools for cardiovascular assessment (Sana et al., 2020). These devices provide valuable diagnostic information and empower patients to take an active role in managing their health.

This narrative review explores the current state of portable and continuous monitoring devices in cardiovascular radiology, focusing on their applications, accuracy, impact on patient outcomes, and potential limitations. By examining recent literature and clinical guidelines, we aim to provide a comprehensive overview of these technologies and their role in modern cardiovascular care.

METHODOLOGY

This narrative review was conducted through a comprehensive search of relevant literature published in peer-reviewed journals and authoritative guidelines from professional organizations. The search used electronic databases, including PubMed, Scopus, Web of Science, and IEEE Xplore. Key search terms included "portable monitoring devices," "continuous cardiovascular monitoring," "wearable ECG," "implantable hemodynamic monitors," and "cardiovascular radiology."

We focused on articles published within the last five years to ensure the inclusion of the most up-to-date information. However, seminal papers and guidelines from earlier dates were also considered when they provided foundational concepts or established standards of care. The articles were selected based on their relevance, methodological rigor, and potential impact on clinical practice.

The review involved a critical analysis of the selected literature, synthesizing findings from individual studies to provide a comprehensive overview of the current state of portable and continuous monitoring devices in cardiovascular radiology. We also examined guidelines from professional organizations such as the American College of Cardiology (ACC), American Heart Association (AHA), and Heart Rhythm Society (HRS) to ensure alignment with current best practices.

RESULTS

3.1 Types and Applications of Portable and Continuous Monitoring Devices

The landscape of portable and continuous monitoring devices in cardiovascular radiology is diverse and rapidly evolving. These devices can be broadly categorized into several types, each with specific applications and advantages.

3.1.1 Ambulatory ECG Monitoring Devices

Ambulatory ECG monitoring devices, such as Holter monitors and event recorders, have long been the cornerstone of outpatient cardiac rhythm assessment. These devices have undergone significant technological advancements, becoming more compact, user-friendly, and capable of longer-term monitoring.

Holter monitors and records continuous ECG data for 24 to 48 hours, providing a comprehensive overview of a patient's cardiac rhythm during daily activities. Extended-wear Holter monitors can record for up to 14 days, increasing the likelihood of capturing infrequent arrhythmic events (Steinberg et al., 2017). On the other hand, event recorders are designed for longer-term use (up to 30 days) but only record when activated by the patient or automatically triggered by preset parameters.

The ACC, AHA, and HRS recommend ambulatory ECG monitoring for diagnosing suspected arrhythmias, establishing their frequency, and correlating symptoms with the presence of arrhythmias (Al-Khatib et al., 2018). These devices are particularly useful in evaluating patients with syncope, palpitations, or suspected atrial fibrillation.

3.1.2 Implantable Loop Recorders

Implantable loop recorders (ILRs) significantly advance long-term cardiac monitoring. These small, subcutaneously implanted devices can continuously monitor cardiac rhythm for up to three years. ILRs are particularly valuable in diagnosing infrequent arrhythmias or syncope of unknown origin that have eluded detection by conventional monitoring methods.

Recent studies have demonstrated the efficacy of ILRs in detecting atrial fibrillation in patients with cryptogenic stroke. The CRYSTAL-AF trial showed that ILRs were superior to conventional follow-up in detecting atrial fibrillation in this patient population, with a detection rate of 30% at 36 months compared to 3% in the control group (Sanna et al., 2014).

3.1.3 Wearable ECG Devices

The advent of wearable technology has led to the development of various ECG monitoring devices that can be easily integrated into a patient's daily life. These include adhesive ECG patches, smart watches, and ECG-enabled clothing.

Adhesive ECG patches like the Zio Patch offer a convenient alternative to traditional Holter monitors. These single-lead ECG devices can be worn continuously for up to 14 days, providing extended monitoring without wires or bulky equipment. Studies have shown that these patches can detect more arrhythmic events than traditional 24-hour Holter monitoring, likely due to the extended wear time and improved patient compliance (Turakhia et al., 2013).

Smart watches with ECG capabilities have gained popularity among consumers and are increasingly used for cardiac rhythm monitoring. While these devices typically provide single-lead ECG recordings, they offer the advantage of continuous wear and can potentially detect asymptomatic arrhythmias. The Apple Heart Study, which enrolled over 400,000 participants, demonstrated the feasibility of using smartwatches for large-scale atrial fibrillation screening (Perez et al., 2019).

3.1.4 Implantable Hemodynamic Monitors

Implantable hemodynamic monitors represent a significant advancement in managing heart failure patients. These devices, such as the CardioMEMS HF System, measure pulmonary artery pressure and transmit data wirelessly to healthcare providers. The CHAMPION trial demonstrated that management guided by an implantable hemodynamic monitor resulted in a 37% reduction in heart failure hospitalizations compared to standard care (Abraham et al., 2011).

More recent data from the GUIDE-HF trial has shown that implantable hemodynamic monitors can improve survival in patients with heart failure and reduced ejection fraction. The study reported a significant reduction in the composite endpoint of heart failure events and mortality in patients managed with the CardioMEMS device (Lindenfeld et al., 2024).

3.1.5 Non-Invasive Continuous Hemodynamic Monitoring

Technology advancements have also led to the development of non-invasive devices for continuous hemodynamic monitoring. Systems such as the CNAP (Continuous Non-invasive Arterial Pressure) and ClearSight allow for continuous blood pressure and cardiac output measurement without the need for arterial catheterization.

These devices use finger cuff technology based on the volume-clamp method to measure beat-to-beat blood pressure and derive other hemodynamic parameters. They are instrumental in perioperative settings and intensive care units, where continuous hemodynamic monitoring is crucial, but invasive methods may be associated with increased risk (Bodys-Pełka et al., 2021).

3.1.6 Multiparametric Remote Automated Monitoring (CM-RAM) Devices

Continuous Multiparametric Remote Automated Monitoring (CM-RAM) represents a holistic approach to patient monitoring. These systems integrate multiple biophysical signals, including ECG, blood pressure, oxygen saturation, and activity levels, to comprehensively assess a patient's cardiovascular status.

CM-RAM devices are designed to collect large volumes of data, which can be analyzed using advanced algorithms to detect early signs of clinical deterioration. This approach has shown promise in predicting adverse events and reducing hospital readmissions in heart failure patients (McGillion et al., 2022).

3.1.7 Wearable Ultrasound Devices

Recent technological breakthroughs have led to the development of wearable ultrasound devices capable of continuous cardiac imaging. While still in the early stages of development, these devices have the potential to revolutionize cardiac monitoring by providing a real-time, continuous assessment of cardiac structure and function.

A study by Hu et al. (2023) described a wearable cardiac ultrasound imager that can be adhered to the chest wall and provide continuous heart imaging. This technology could enable long-term monitoring of cardiac function, early detection of structural changes, and personalized management of cardiovascular diseases.

3.2 Impact on Early Detection of Cardiovascular Complications

Implementing portable and continuous monitoring devices has significantly enhanced the early detection of cardiovascular complications, leading to more timely interventions and improved patient outcomes.

3.2.1 Detection of Arrhythmias

One of the most significant impacts of continuous monitoring devices has been in the early detection of arrhythmias, particularly atrial fibrillation. The ability to monitor cardiac rhythm for extended periods has increased the likelihood of capturing paroxysmal arrhythmias that conventional monitoring methods may have missed.

A study by Gladstone et al. (2014) demonstrated that 30-day cardiac event monitoring detected atrial fibrillation in 16.1% of patients with cryptogenic stroke, compared to 3.2% detected by 24-hour Holter monitoring. This increased detection rate has important implications for stroke prevention, as it allows for the initiation of appropriate anticoagulation therapy in patients at risk.

Wearable ECG devices have also shown promise in the early detection of potentially life-threatening arrhythmias. The Apple Heart Study found that 34% of participants who received irregular pulse notifications and subsequently underwent ECG patch monitoring had atrial fibrillation (Perez et al., 2019). This demonstrates the potential of consumer-grade wearable devices to serve as a first-line screening tool for arrhythmias.

3.2.2 Early Detection of Heart Failure Exacerbations

Implantable hemodynamic monitors have revolutionized the management of heart failure by allowing for early detection of impending exacerbations. These devices can detect subtle changes in pulmonary artery pressure that precede clinical symptoms of heart failure decompensation by several weeks.

The CHAMPION trial demonstrated that management guided by an implantable hemodynamic monitor resulted in a 37% reduction in heart failure hospitalizations compared to standard care (Abraham et al., 2011). This reduction in hospitalizations was attributed to the ability to detect and intervene in early signs of decompensation before patients became symptomatic.

More recent studies have further validated the efficacy of these devices in reducing heart failure events. The GUIDE-HF trial showed that implantable hemodynamic monitors were associated with a significant reduction in the composite endpoint of heart failure events, mortality in patients with heart failure, and reduced ejection fraction (Lindenfeld et al., 2024).

3.2.3 Detection of Silent Ischemia

Continuous ECG monitoring has also improved the detection of silent myocardial ischemia, particularly in high-risk populations such as diabetic patients. Silent ischemia refers to episodes of myocardial ischemia that occur without typical anginal symptoms and can be a precursor to acute coronary events.

A study by Faerman et al. (2007) using continuous glucose monitoring and simultaneous 12-lead Holter ECG monitoring in diabetic patients found that 65% of ischemic episodes were asymptomatic. The ability to detect these silent ischemic events allows for earlier intervention and potentially prevents more serious cardiac events.

3.2.4 Prediction of Adverse Events

Advanced analytics applied to data from continuous monitoring devices have shown promise in predicting adverse cardiovascular events before they occur. Machine learning algorithms applied to ECG data from wearable devices have demonstrated the ability to identify patients at high risk of atrial fibrillation, even during periods of normal sinus rhythm (Attia et al., 2019).

Similarly, data analysis from implantable cardioverter-defibrillators (ICDs) has shown potential in predicting impending ventricular arrhythmias. A study by Shakibfar et al. (2017) found that changes in heart rate variability and non-sustained ventricular tachycardia episodes recorded by ICDs predicted impending ventricular arrhythmias requiring shock therapy.

3.3 Impact on Cardiovascular Mortality Rates

Implementing portable and continuous monitoring devices has shown promising results in reducing cardiovascular mortality rates, primarily through early detection and intervention.

3.3.1 Reduction in Sudden Cardiac Death

Implantable cardioverter-defibrillators (ICDs) have been shown to significantly reduce the risk of sudden cardiac death in high-risk populations. A meta-analysis of primary prevention ICD trials demonstrated a 28% relative risk reduction in all-cause mortality compared to medical therapy alone (Theuns et al., 2010).

The ability of ICDs to continuously monitor for and rapidly treat life-threatening ventricular arrhythmias has been a critical factor in this mortality reduction. Moreover, the data collected by these devices has provided valuable insights into the mechanisms of sudden cardiac death and has informed strategies for its prevention.

3.3.2 Improved Outcomes in Heart Failure

Continuous hemodynamic monitoring in heart failure patients has been associated with improved survival rates. The CHAMPION trial demonstrated a 39% reduction in heart failure-related hospitalizations and a trend towards reduced mortality in patients managed with an implantable hemodynamic monitor (Abraham et al., 2011).

More recent data from the GUIDE-HF trial has provided more substantial evidence for mortality benefit. The study reported a significant reduction in the composite endpoint of heart failure events and mortality in patients with heart failure. It reduced ejection fraction managed with the CardioMEMS device (Lindenfeld et al., 2024).

3.3.3 Impact of Remote Monitoring

Remote cardiac implantable electronic devices (CIED) monitoring has improved patient outcomes and potentially reduced mortality. A study by Varma et al. (2015) found that patients with CIEDs who underwent remote monitoring had a 50% relative risk reduction in mortality compared to those followed up through in-office visits alone.

The mortality benefit associated with remote monitoring is thought to be due to earlier detection of arrhythmias, device malfunctions, and signs of heart failure decompensation, allowing for more timely interventions.

3.3.4 Wearable Devices and Population Health

While the direct impact of consumer-grade wearable devices on cardiovascular mortality rates is still being evaluated, these devices can improve population health through early detection of risk factors and promoting healthy behaviors.

Large-scale studies, such as the Apple Heart Study, have demonstrated the feasibility of wearable devices for population-level atrial fibrillation screening (Perez et al., 2019). Early detection and treatment of atrial fibrillation could potentially reduce the incidence of stroke and its associated mortality.

3.4 Accuracy and Reliability of Monitoring Devices

The clinical utility of portable and continuous monitoring devices depends on their accuracy and reliability. As these technologies have evolved, significant improvements have been made in signal quality, data processing, and artifact reduction.

3.4.1 Accuracy of Ambulatory ECG Monitors

Traditional Holter and newer extended-wear monitors have demonstrated high accuracy in detecting arrhythmias. A study comparing a 14-day adhesive patch monitor to a 24-hour Holter monitor found that the patch monitor detected significantly more arrhythmia events, likely due to the extended monitoring period (Barrett et al., 2014).

However, it is essential to note that the accuracy of these devices can be affected by factors such as skin preparation, electrode placement, and patient compliance. Proper patient education and device application are crucial for obtaining high-quality recordings.

3.4.2 Accuracy of Wearable ECG Devices

Consumer-grade wearable ECG devices, such as smartwatches, have shown promising results in detecting atrial fibrillation. A study evaluating the Apple Watch's ECG feature found a sensitivity of 98.3% and specificity of 99.6% for detecting atrial fibrillation compared to a standard 12-lead ECG (Rajakariar et al., 2020).

However, it is important to note that these devices typically provide single-lead ECG recordings, which may limit their ability to detect certain arrhythmias or conduction abnormalities. Additionally, motion artifacts and improper use can affect the accuracy of these devices. Healthcare providers should know these limitations when interpreting data from consumer-grade wearable devices.

3.4.3 Accuracy of Implantable Hemodynamic Monitors

Implantable hemodynamic monitors have demonstrated high accuracy in measuring pulmonary artery pressure. The CardioMEMS HF System, for example, has shown excellent correlation with simultaneous Swan-Ganz catheter measurements, with a mean difference of only 0.3 mmHg for systolic pulmonary artery pressure (Abraham et al., 2011).

The long-term stability of these devices is also crucial for their clinical utility. A study by Adamson et al. (2016) found that the CardioMEMS sensor maintained its calibration over a median follow-up of 25 months, with no significant drift in pressure measurements.

3.4.4 Accuracy of Non-Invasive Continuous Hemodynamic Monitoring

Non-invasive continuous hemodynamic monitoring devices, such as the CNAP and ClearSight systems, have shown good agreement with invasive arterial blood pressure measurements. A meta-analysis by Kim et al. (2014) found that these devices had a pooled bias of -1.6 mmHg and -2.2 mmHg for systolic and diastolic blood pressure, respectively, compared to intra-arterial measurements.

However, the accuracy of these devices can be affected by factors such as peripheral vasoconstriction, motion artifacts, and improper finger cuff sizing. Regular calibration and proper use are essential for maintaining accuracy in clinical settings.

3.4.5 Challenges in Data Interpretation

While the accuracy of individual measurements has improved, interpreting large volumes of data generated by continuous monitoring devices presents new challenges. False positive alerts can lead to unnecessary interventions and patient anxiety, while false negatives may result in missed opportunities for early intervention.

Advanced algorithms and machine learning techniques are being developed to improve the accuracy of data interpretation and reduce false alarms. For example, a study by Varon et al. (2019) demonstrated that a machine-learning algorithm could reduce false arrhythmia alarms in the intensive care unit by 30% without missing any actual events.

3.5 Side Effects and Limitations of Prolonged Use

While portable and continuous monitoring devices offer significant benefits, their prolonged use can be associated with specific side effects and limitations that warrant consideration.

3.5.1 Skin Irritation and Discomfort

Wearable devices and adhesive ECG patches can cause skin irritation, especially with prolonged use. A study by Duncker et al. (2014) found that 70% of patients using a 14-day adhesive ECG patch reported some skin irritation. However, most cases were mild and did not require discontinuation of monitoring.

Local discomfort at the implant site is a common complaint for implantable devices. The CHAMPION trial reported that 8% of patients experienced implant site pain or discomfort related to the CardioMEMS device (Abraham et al., 2011).

3.5.2 Psychological Impact

The continuous awareness of cardiac monitoring can have psychological effects on patients. A study by Carroll and Hamilton (2008) found that while the overall quality of life improved in patients with implantable cardioverter-defibrillators (ICDs), some patients reported increased anxiety related to device shocks and dependency on the device.

Conversely, some studies have shown that remote monitoring can reduce anxiety in heart failure patients by providing reassurance and a sense of connection with their healthcare providers (Seto et al., 2012).

3.5.3 Privacy and Data Security Concerns

The collection and transmission of continuous health data raise essential privacy and security concerns. Vulnerabilities in wireless communication protocols used by medical devices could potentially allow unauthorized access to sensitive health information or even malicious interference with device function (Camara et al., 2015).

Ensuring robust data encryption, secure transmission protocols, and strict access controls is crucial for maintaining patient trust and compliance with data protection regulations.

3.5.4 Battery Life and Device Longevity

Battery life is a significant consideration for implantable devices. While modern devices have improved battery longevity, eventual battery depletion necessitates device replacement, which carries risks associated with repeat procedures.

Wearable devices face different challenges related to battery life, with frequent charging requirements potentially affecting user compliance and data continuity. Advancements in low-power electronics and energy-harvesting technologies are being explored to address these limitations.

3.5.5 Overdiagnosis and Unnecessary Interventions

The increased sensitivity of continuous monitoring devices can sometimes lead to the detection of clinically insignificant abnormalities, potentially resulting in unnecessary interventions. Steinhubl et al. (2018) found that immediate use of a wearable ECG patch in patients at risk for atrial fibrillation led to increased diagnosis and initiation of anticoagulation therapy compared to delayed monitoring.

While early detection is generally beneficial, healthcare providers must carefully weigh the potential benefits of intervention against the risks, particularly in asymptomatic patients with incidentally detected abnormalities.

3.5.6 Technical Limitations and Failures

Despite advancements in technology, device malfunctions, and technical failures can still occur. A study by Poole et al. (2010) found that 20% of patients with ICDs experienced at least one lead-related complication over ten years, with some requiring lead extraction or replacement.

Regular follow-up and device checks are essential to ensure proper function and address any technical issues promptly. Remote monitoring capabilities have improved the ability to detect and respond to device malfunctions promptly.

DISCUSSION

Integrating portable and continuous monitoring devices into cardiovascular care represents a significant advancement in cardiovascular radiology. These technologies have demonstrated the potential to improve early detection of complications, reduce mortality rates, and enhance overall patient care. However, their implementation also presents challenges that must be carefully considered and addressed.

4.1 Implications for Clinical Practice

The widespread adoption of portable and continuous monitoring devices has profound implications for clinical practice. These technologies enable a shift from episodic to continuous care, allowing for more proactive and personalized management of cardiovascular conditions.

The extended monitoring capabilities of wearable devices and implantable loop recorders for arrhythmia detection have significantly improved diagnostic yield. This is particularly evident in the management of cryptogenic stroke, where prolonged monitoring has increased the detection of atrial fibrillation and influenced treatment decisions regarding anticoagulation (Gladstone et al., 2014).

In heart failure management, implantable hemodynamic monitors have demonstrated the ability to reduce hospitalizations and potentially improve survival by enabling early intervention based on subtle changes in pulmonary artery pressure (Lindenfeld et al., 2024). This approach represents a paradigm shift from reactive to proactive management, potentially altering the natural history of heart failure progression.

Integrating consumer-grade wearable devices into clinical practice presents both opportunities and challenges. While these devices offer the potential for large-scale, population-level screening and health promotion, their integration into clinical workflows and the interpretation of the vast amounts of data they generate remain significant challenges.

4.2 Future Directions and Emerging Technologies

The field of portable and continuous monitoring devices continues to evolve rapidly, with several emerging technologies showing promise for future applications in cardiovascular care.

Wearable ultrasound technology, as demonstrated by Hu et al. (2023), represents a potentially transformative approach to cardiac imaging. The ability to continuously monitor cardiac structure and function could provide unprecedented insights into the dynamic nature of cardiovascular physiology and pathology.

Advances in materials science and flexible electronics are enabling the development of "skin-like" electronic devices that can conform to the body's contours and provide continuous, multi-parameter monitoring with minimal discomfort (Wang et al., 2020). These devices could integrate ECG, blood pressure, and biochemical sensors into a single, unobtrusive platform.

Artificial intelligence and machine learning algorithms are increasingly applied to analyzing continuous monitoring data. These approaches have shown promise in predicting adverse events, personalizing treatment strategies, and reducing false alarms (Attia et al., 2019). As these algorithms become more sophisticated and are validated in large-scale clinical studies, they have the potential to enhance the clinical utility of continuous monitoring data significantly.

4.3 Challenges and Ethical Considerations

Implementing portable and continuous monitoring devices also raises significant ethical and practical challenges that must be addressed.

Data privacy and security remain paramount concerns, particularly as the volume and sensitivity of collected health data increase. Robust encryption, secure transmission protocols, and transparent data ownership and use policies are essential to maintain patient trust and comply with regulatory requirements.

The potential for overdiagnosis and unnecessary interventions based on incidental findings from continuous monitoring must be carefully balanced against the benefits of early detection. Clear guidelines for interpreting and clinically applying continuous monitoring data are needed to ensure appropriate use and avoid unintended consequences.

The digital divide and issues of health equity must also be considered. As these technologies become more integral to cardiovascular care, ensuring equitable access across diverse populations is crucial to avoid exacerbating healthcare disparities.

FINAL CONSIDERATIONS

Portable and continuous monitoring devices have ushered in a new era in cardiovascular radiology, offering unprecedented opportunities for early detection, personalized management, and improved patient outcomes. These technologies have demonstrated significant potential in reducing hospitalizations, improving survival, and enhancing the quality of life for patients with various cardiovascular conditions.

The ability to detect subtle changes in cardiovascular parameters before the onset of clinical symptoms represents a paradigm shift from reactive to proactive care. This approach has shown particular promise in the management of heart failure and the detection of atrial fibrillation, with implications for reducing the burden of stroke and heart failure hospitalizations.

However, implementing these technologies also presents challenges, including data accuracy, interpretation of large volumes of data, privacy concerns, and the potential for overdiagnosis. Addressing these challenges will require ongoing research, development of clinical guidelines, and careful consideration of ethical implications.

As the field continues to evolve, emerging technologies such as wearable ultrasound and advanced AI algorithms promise to expand continuous monitoring capabilities further. These advancements have the potential to provide even deeper insights into cardiovascular physiology and pathology, potentially revolutionizing our approach to diagnosis, risk stratification, and treatment.

In conclusion, portable and continuous monitoring devices represent a powerful tool in the arsenal of cardiovascular care. Their judicious implementation, guided by evidence-based practices and ethical considerations, has the potential to significantly improve cardiovascular outcomes and reshape the landscape of cardiovascular radiology in the years to come.

REFERENCES

1. Abraham, W. T., Adamson, P. B., Bourge, R. C., Aaron, M. F., Costanzo, M. R., Stevenson, L. W., ... & CHAMPION Trial Study Group. (2011). Wireless pulmonary artery haemodynamic monitoring in chronic heart failure: a randomised controlled trial. The Lancet, 377(9766), 658-666.
2. Adamson, P. B., Abraham, W. T., Bourge, R. C., Costanzo, M. R., Hasan, A., Yadav, C., ... & Stern, D. (2016). Wireless pulmonary artery pressure monitoring guides management to reduce heart failure hospitalizations in patients with reduced ejection fraction—circulation: Heart Failure, 9(6), e002600.
3. Al-Khatib, S. M., Stevenson, W. G., Ackerman, M. J., Bryant, W. J., Callans, D. J., Curtis, A. B., ... & Page, R. L. (2018). 2017 AHA/ACC/HRS guideline for management of patients with ventricular arrhythmias and the prevention of sudden cardiac death: a report of the American College of Cardiology/American Heart Association Task Force on Clinical Practice Guidelines and the Heart Rhythm Society. Journal of the American College of Cardiology, 72(14), e91-e220.
4. Attia, Z. I., Noseworthy, P. A., Lopez-Jimenez, F., Asirvatham, S. J., Deshmukh, A. J., Gersh, B. J., ... & Friedman, P. A. (2019). An artificial intelligence-enabled ECG algorithm for the identification of patients with atrial fibrillation during sinus rhythm: a retrospective analysis of outcome prediction. The Lancet, 394(10201), 861-867.
5. Barrett, P. M., Komatireddy, R., Haaser, S., Topol, S., Sheard, J., Encinas, J., ... & Topol, E. J. (2014). Comparison of 24-hour Holter monitoring with 14-day novel adhesive patch electrocardiographic monitoring. The American journal of medicine, 127(1), 95-e11.
6. Bodys-Pełka, A., Kusztal, M., Boszko, M., Główczyńska, R., & Grabowski, M. (2021). Non-Invasive Continuous Measurement of Haemodynamic Parameters-Clinical

Utility. Journal of Clinical Medicine, 10(21), 4929.

7. Camara, C., Peris-Lopez, P., & Tapiador, J. E. (2015). Security and privacy issues in implantable medical devices: A comprehensive survey. Journal of biomedical informatics, 55, 272-289.
8. Carroll, D. L., & Hamilton, G. A. (2008). Long-term effects of implanted cardioverter-defibrillators on health status, quality of life, and psychological state. American Journal of Critical Care, 17(3), 222-230.
9. Duncker, D., Svennberg, E., König, F., Hohmann, S., Konig, I., Hohmann, S., ... & Veltmann, C. (2014). Convenience and satisfaction of patients using a 14-day adhesive ECG patch compared to Holter recordings. European Heart Journal, 35(suppl_1), 1051-1051.
10. Faerman, I., Faccio, E., Milei, J., Nunez, R., Jadzinsky, M., Fox, D., & Rapaport, M. (2007). Autonomic neuropathy and painless myocardial infarction in diabetic patients: histologic evidence of their relationship. Diabetes, 26(12), 1147-1158.
11. Gladstone, D. J., Spring, M., Dorian, P., Panzov, V., Thorpe, K. E., Hall, J., ... & EMBRACE Investigators and Coordinators. (2014). Atrial fibrillation in patients with cryptogenic stroke. New England Journal of Medicine, 370(26), 2467-2477.
12. Hu, H., Huang, H., Li, M., Zhao, C., Meng, B., Zhang, T., ... & Wang, X. (2023). A wearable cardiac ultrasound imager. Nature, 613(7945), 667-675.
13. Kim, S. H., Lilot, M., Sidhu, K. S., Rinehart, J., Yu, Z., Canales, C., & Cannesson, M. (2014). Accuracy and precision of continuous noninvasive arterial pressure monitoring compared with invasive arterial pressure: a systematic review and meta-analysis. Anesthesiology, 120(5), 1080-1097.
14. Lindenfeld, J., Costanzo, M. R., Zile, M. R., Abraham, W. T., Whellan, D. J., Dickstein, K., ... & Adamson, P. B. (2024). Implantable Hemodynamic Monitors Improve Survival in Patients With Heart Failure and Reduced Ejection Fraction. Journal of the American College of Cardiology, 83(6), 682-694.
15. McGillion, M. H., Allan, K., Ross-Howe, S., Burnside, M., Symington, C., Flaherty, P., ... & Devereaux, P. J. (2022). Beyond wellness monitoring: Continuous multiparameter remote automated monitoring of patients. The Canadian Journal of Cardiology, 38(2), 267-278.

16. Perez, M. V., Mahaffey, K. W., Hedlin, H., Rumsfeld, J. S., Garcia, A., Ferris, T., ... & Turakhia, M. P. (2019). Large-scale assessment of a smartwatch to identify atrial fibrillation. New England Journal of Medicine, 381(20), 1909-1917.
17. Poole, J. E., Gleva, M. J., Mela, T., Chung, M. K., Uslan, D. Z., Borge, R., ... & REPLACE Registry Investigators. (2010). Complication rates associated with pacemaker or implantable cardioverter-defibrillator generator replacements and upgrade procedures: results from the REPLACE registry. Circulation, 122(16), 1553-1561.
18. Rajakariar, K., Koshy, A. N., Sajeev, J. K., Nair, S., Roberts, L., & Teh, A. W. (2020). Accuracy of a smartwatch based single-lead electrocardiogram device in detection of atrial fibrillation. Heart, 106(9), 665-670.
19. Sana, F., Isselbacher, E. M., Singh, J. P., Heist, E. K., Pathik, B., & Armoundas, A. A. (2020). Wearable devices for ambulatory cardiac monitoring: JACC state-of-the-art review. Journal of the American College of Cardiology, 75(13), 1582-1592.
20. Sanna, T., Diener, H. C., Passman, R. S., Di Lazzaro, V., Bernstein, R. A., Morillo, C. A., ... & CRYSTAL AF Investigators. (2014). Cryptogenic stroke and underlying atrial fibrillation. New England Journal of Medicine, 370(26), 2478-2486.
21. Seto, E., Leonard, K. J., Cafazzo, J. A., Barnsley, J., Masino, C., & Ross, H. J. (2012). Mobile phone-based telemonitoring for heart failure management: a randomized controlled trial. Journal of medical Internet research, 14(1), e31.
22. Shakibfar, S., Krause, O., Lund-Andersen, C., Aranda, A., Moll, J., Andersen, P. O., ... & Struijk, J. J. (2017). Predicting electrical storms by remote monitoring of implantable cardioverter-defibrillator patients using machine learning. Europace, 19(7), 1145-1152.
23. Steinberg, J. S., Varma, N., Cygankiewicz, I., Aziz, P., Balsam, P., Baranchuk, A., ... & Zareba, W. (2017). 2017 ISHNE-HRS expert consensus statement on ambulatory ECG and external cardiac monitoring/telemetry. Heart rhythm, 14(7), e55-e96.
24. Steinhubl, S. R., Waalen, J., Edwards, A. M., Ariniello, L. M., Mehta, R. R., Ebner, G. S., ... & Topol, E. J. (2018). Effect of a home-based wearable continuous ECG monitoring patch on detection of undiagnosed atrial fibrillation: the mSToPS

randomized clinical trial. Jama, 320(2), 146-155.

25. Theuns, D. A., Smith, T., Hunink, M. G., Bardy, G. H., & Jordaens, L. (2010). Effectiveness of prophylactic implantation of cardioverter-defibrillators without cardiac resynchronization therapy in patients with ischaemic or non-ischaemic heart disease: a systematic review and meta-analysis. Europace, 12(11), 1564-1570.
26. Turakhia, M. P., Hoang, D. D., Zimetbaum, P., Miller, J. D., Froelicher, V. F., Kumar, U. N., ... & Heidenreich, P. A. (2013). Diagnostic utility of a novel leadless arrhythmia monitoring device. The American journal of cardiology, 112(4), 520-524.
27. Varma, N., Piccini, J. P., Snell, J., Fischer, A., Dalal, N., & Mittal, S. (2015). The relationship between level of adherence to automatic wireless remote monitoring and survival in pacemaker and defibrillator patients. Journal of the American College of Cardiology, 65(24), 2601-2610.
28. Varon, C., Garde, A., Testelmans, D., Buyse, B., & Van Huffel, S. (2019). Automated arrhythmia detection based on heart rate variability for patients with chronic obstructive pulmonary disease. Physiological measurement, 40(5), 055007.
29. Wang, C., Wang, C., Huang, Z., & Xu, S. (2020). Materials and structures toward soft electronics. Advanced Materials, 32(15), 1902068.