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REVIEW

Wearable biosensors for cardiovascular monitoring leveraging nanomaterials

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Abstract

The medical domain is currently experiencing a significant shift from centralized healthcare models to home-based and personalized monitoring paradigms, particularly in the realm of cardiovascular monitoring. This move towards wearable systems is aimed at serving a wider population, reducing hospital resources' burden, and cutting healthcare costs. There is growing interest in leveraging advanced nanomaterials to develop cutting-edge wearable biosensors for cardiovascular applications. These devices offer precise, real-time, and continuous data collection, which is crucial for creating personalized therapeutic interventions. Central to this innovation is the integration of various nanostructures with advanced biosensing techniques and microelectronics. These nanostructures play a pivotal role in enhancing preventative medical care by facilitating early diagnosis and management of critical health conditions. This review explores the latest advancements in wearable biosensors and assesses their role in monitoring cardiac vitals. It provides a comprehensive analysis of the materials, design principles, functional mechanisms, and recent breakthroughs related to these sensors, focusing on their applications in monitoring cardiac activity, measuring blood pressure, assessing pulse wave velocity, and detecting biomarkers.

Keywords Wearable biosensors · Cardiovascular healthcare · Nanomaterials · Real-time monitoring

1 Introduction

Cardiovascular diseases (CVDs) are the leading cause of death worldwide, accounting for approximately 31% of all mortalities, or about 17.9 million deaths annually [1–4]. The often covert nature of CVDs, which can escalate to acute events such as myocardial infarctions or strokes without prior detection, underscores the need for continual cardiovascular monitoring [5]. In this context, the electrocardiogram (ECG), which diagnoses various cardiac conditions by analyzing the heart's electrical activity, is of paramount importance [6]. However, the ECG's limitations in detecting unpredicted and time-sensitive cardiac anomalies highlight the pressing need for advanced wearable technologies that enable rapid and precise CVD monitoring [7, 8].

Over the past decade, there has been a significant interdisciplinary effort to incorporate nanomaterials into wearable biosensor development. This stems from the realization that materials at the nanoscale possess unique properties that blend characteristics of bulk solids with those of atomic or molecular systems [9, 10]. Nanomaterials, defined by their dimensions ranging from 1 to 100 nm, are seen as key

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enhancers of detection sensitivity, signal fidelity, and stability in biosensing applications [11, 12]. Recent advancements exemplify the potential of bimetallic nickel-cobalt oxide/carbon composites, demonstrating their superior electromagnetic wave absorption capabilities. The meticulous design of these nanocomposites, characterized by their unique urchin-shaped morphology, underscores the significant role of nano-architectures in amplifying the functional properties of biosensors. The incorporation of such nanomaterials into biosensing platforms could markedly improve the detection and monitoring of cardiovascular conditions, by harnessing the enhanced electromagnetic interaction at the nanoscale for more sensitive and stable biomarker analysis [13, 14]. A notable feature of nanomaterials is their vast specific surface area, which allows for the capture of highly sensitive signals and the enhancement of signal detection in small sample volumes, robust sensing probes, and miniaturized devices [15–30].

The integration of nanomaterials into the development of wearable biosensors for cardiovascular monitoring represents a significant advancement in medical technology, blurring the lines between nanotechnology and biomedical engineering [15, 18–20, 22, 24–30]. This interdisciplinary effort over the last decade has underscored the transformative potential of nanomaterials, defined by their dimensions ranging from 1 to 100 nm. These materials effectively bridge the divide between bulk solids and atomic or molecular systems, embodying unique characteristics that are specifically harnessed in biosensing applications. The intrinsic properties of nanomaterials, notably their extensive specific surface area, are critical to boosting biosensor performance [11, 12]. This observation is further substantiated by recent research on flexible and biocompatible polystyrene/multi-walled carbon nanotubes (PS/MWCNTs) films, which have demonstrated high permittivity and low loss, key factors for enhancing the sensitivity and reliability of wearable biosensors for cardiovascular monitoring [31]. Such advancements in material science not only pave the way for the next generation of biosensors but also highlight the pivotal role of carefully engineered nanocomposites in achieving optimal sensor performance. Through these advancements, nanomaterials are revolutionizing cardiovascular health management, heralding new possibilities for early detection, continuous monitoring, and potentially profound effects on patient care and outcomes.

Furthermore, the application of nanomaterials in biosensors notably improves signal fidelity and stability, key factors for dependable and precise monitoring systems [16, 17, 21, 23]. These enhancements stem from the unique electrical, chemical, and physical properties of nanomaterials, which promote improved signal transduction and minimize background noise. Consequently, biosensors are capable of detecting slight fluctuations in physiological markers that indicate cardiovascular health or disease states. The integration of nanomaterials has also driven innovation in device miniaturization and the development of robust sensing probes. These advancements have culminated in the creation of lightweight, non-invasive, and user-friendly devices capable of consistently monitoring cardiovascular health metrics in real-world settings, beyond the confines of traditional healthcare facilities. Such devices play a crucial role in enabling patients to proactively manage their health, providing instant insights into their cardiovascular condition.

The convergence of nanotechnology with biosensor development has initiated a new era of cardiovascular monitoring, leveraging the distinctive properties of nanomaterials to significantly enhance wearable biosensor performance [32, 33]. This cross-disciplinary strategy not only broadens the scope of biosensing technologies but also sets the stage for future advancements in personalized healthcare, highlighting the pivotal role of nanomaterials in advancing the efficacy, sensitivity, and accessibility of cardiovascular monitoring devices. Through these advancements, nanomaterials are revolutionizing cardiovascular health management, heralding new possibilities for early detection, continuous monitoring, and potentially profound effects on patient care and outcomes.

This review focuses on wearable biosensors designed for cardiovascular monitoring, particularly emphasizing the integration of nanomaterials. It concisely covers essential aspects of cardiovascular monitoring metrics, advanced nanomaterials, the fabrication and usage of wearable biosensors, their specific applications in monitoring cardiovascular health, and their clinical incorporation into cardiovascular healthcare. (Fig. 1) [34–38]. Additionally, the review engages in an analytical discussion on the challenges and prospects of nanomaterial-based wearable biosensors and their significant implications for cardiovascular health management [39].

To further augment the sensitivity and performance of wearable biosensors in cardiovascular monitoring, the exploration of hierarchical nanocomposites, such as Ni(OH)2/rGO, presents a promising avenue. This composite material, synthesized through chemical deposition on Ni foam, exhibits a nanoflower-like morphology comprising ultrathin nanosheets or nanopetals with a porous structure. The incorporation of reduced graphene oxide (rGO) enhances the electrical conductivity, significantly benefiting the proton transfer process during sensor operation. Such materials can potentially improve the detection of cardiovascular biomarkers, offering higher sensitivity and rapid response times, critical for early diagnosis and continuous health monitoring.

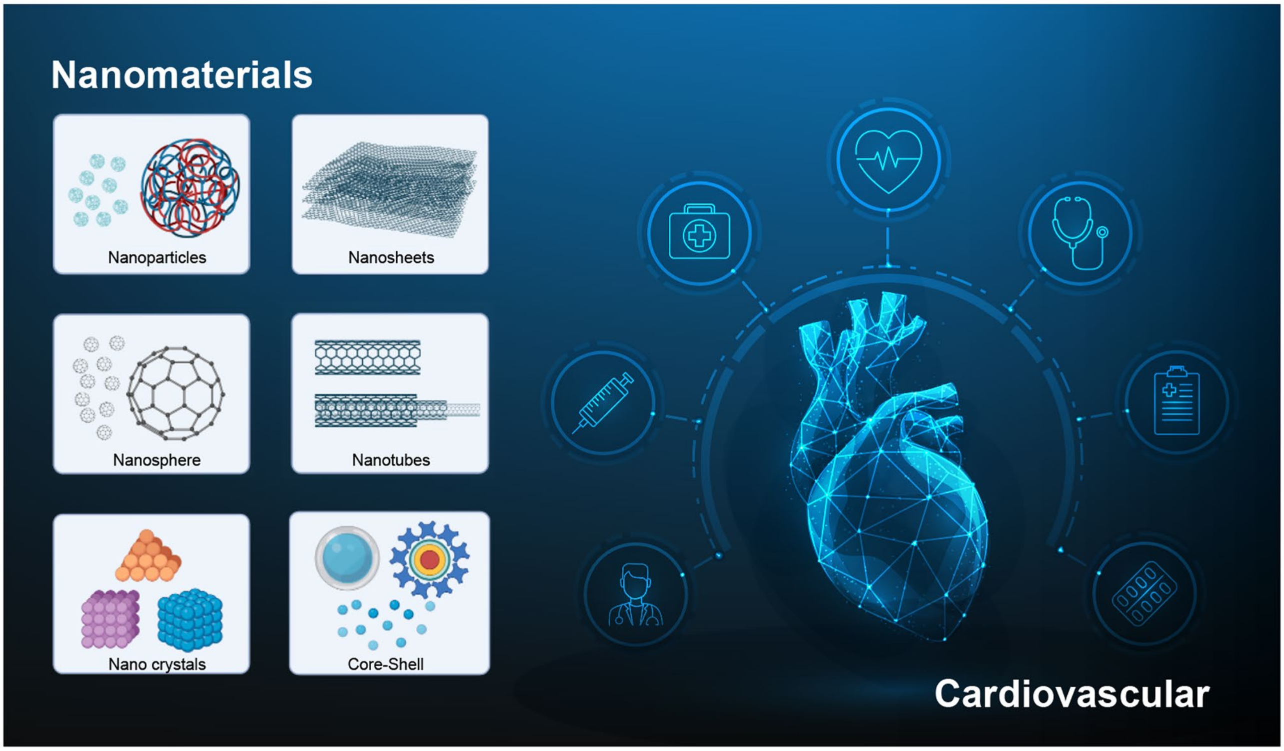

Fig. 1 Schematic diagram illustrating the topics covered in this review on applications of nanomaterials in wearable biosensors for cardiovascular monitoring

2 Cardiovascular monitoring metrics

2.1 Heart rate

Heart rate (HR), which is indicative of the number of cardiac cycles per minute, plays an essential role in cardiovascular monitoring [35, 40, 41]. It is well-supported by numerous epidemiological studies that resting HR is a critical indicator for evaluating cardiac function. Individuals with a high level of cardiovascular fitness usually have a resting HR of less than 60 beats per minute (BPM) [42], whereas an increased resting HR, exceeding 90 BPM, is associated with a higher risk of cardiovascular-related mortality [43, 44]. Pharmacological interventions can lead to a decrease in HR. Therefore, the ability to consistently, instantly, and accurately track HR is crucial for both diagnosing and managing CVDs. Each cardiac cycle generates a pulse wave that travels once through the circulatory system, making the total arterial pulses per minute equivalent to the HR [45]. Wearable biosensors are capable of detecting these biomechanical signals and reconstructing the pulse waveforms [46, 47]. By counting the apical peaks every minute, these biometric sensors provide precise HR measurements. When these devices are combined with units that manage signals and transfer data, real-time HR can be displayed on personal devices [48]. Wearable biosensors detect biomechanical signals and reconstruct pulse waveforms to enable accurate HR measurements by counting the apical peaks per minute [46, 47]. When integrated with signal management and data transfer units, live HR data can be displayed on personal devices [48]. Consequently, HR emerges as an easily measured clinical parameter, particularly relevant for wearable biosensors, which may have limited sensitivity and difficulty discerning irregularities or multi-peaked complexities in pulse waveforms.

2.2 Blood pressure

Blood pressure (BP) measures the force that circulating blood exerts against the walls of the major arteries [12, 49]. It is typically represented by two values: systolic and diastolic pressures, with normal ranges being less than 120 mmHg for systolic and less than 80 mmHg for diastolic [50]. Conversely, high and low BP values indicate hypertension (HTN) and hypotension, respectively. According to the World Health Organization, approximately 1.13 billion people worldwide are affected by hypertension [51]. Diagnosis largely relies on BP measurements. Traditional BP cuffs, through standard, can cause discomfort or even tissue damage due to the pressure they apply on the arm. Furthermore, these measurements are not continuous and can be impractical during daily activities. Thus, there is a significant need for a method that is both wearable and reliable for prolonged BP monitoring, particularly for individuals with chronic conditions [52, 53].

2.3 Pulse wave velocity

Pulse wave velocity (PWV) is a measure of arterial health, indicating the speed at which the systolic contraction wave moves through the circulatory system [54, 55]. Recognized as a powerful diagnostic tool for CVDs, PWV increases as arterial walls thicken or become less elastic due to disease or aging [54]. PWV is measured by calculating the distance and time it takes for a pulse to travel between two arterial points.

The waveform typically includes three main peaks: the systolic peak, inflection wave peak, and diastolic peak, which may become less distinct in older individuals or those with compromised arterial health. From these peaks, various metrics can be derived, such as the radial artery augmentation index, allowing individuals to assess their cardiovascular health against standard references. However, relying solely on weak pulse waveforms for diagnosis can reduce accuracy. Wearable biosensors provide accurate and continuous PWV measurements [7, 56], which, when compared to established norms, aid in effective screening and early detection of CVDs. This is particularly important in elderly care, where a PWV exceeding 10 m/s may indicate underlying organ damage [57]. Exploring PWV analytically offers insights into the effects of aging and various factors on arterial health.

2.4 Biomarkers

Although various biofluids present opportunities for analysis, there are significant challenges when integrating them with wearable sensing technologies [58–60]. Blood and interstitial fluid (IF) allow for continuous monitoring through implanted devices but are difficult to access non-invasively with wearable technology. The potential for discomfort and irritation could lead to reflex tears, complicating sensor readings [61]. While urine offers analytical possibilities, urine-based sensors do not fit well with wearable configurations. Similarly, saliva, though analytically useful, can be heavily influenced by recent food or drink intake, limiting the scope of physiological data it can provide [62].

In contrast, sweat emerges as a particularly promising medium for wearable sensing due to its non-invasive collection and the ability to be generated on demand, especially from easily accessible parts of the body [63, 64]. This makes sweat ideal for continuous monitoring. Sensors can be placed close to areas of sweat production for quick detection of analytes before they degrade. Despite its own set of measurement and interpretation challenges, sweat's advantages have elevated its status in the realm of wearable technology. Components of sweat, such as glucose, sodium, potassium, lactate, and certain proteins, offer vital insights into an individual's physiological state and health conditions [58, 65, 66].

Among these biomarkers, cardiac troponins (cTns), particularly cardiac troponin I (cTnI) and cardiac troponin T (cTnT), have emerged as cornerstone biomarkers for the diagnosis and risk stratification of acute myocardial infarction (AMI) [67]. The highly specific nature of cTns for cardiac injury, coupled with advancements in nanomaterial-based sensors, has enabled the development of wearable biosensors capable of detecting these biomarkers at ultra-low concentrations in real time. This capability represents a paradigm shift in the monitoring and management of cardiovascular diseases, allowing for timely interventions even before classical symptoms manifest. The integration of biosensors for the detection of N-terminal pro b-type natriuretic peptide (NT-proBNP), a biomarker for heart failure, offers a comprehensive approach to monitoring the cardiac health of patients with chronic conditions [68]. By enabling continuous, non-invasive monitoring of these key biomarkers, wearable biosensors can significantly enhance patient care. They provide clinicians with invaluable data for making informed decisions and tailoring treatments to individual patient needs, thus representing a significant step forward in personalized medicine. Non-invasive sweat-sensing technologies carefully select and measure these analytes based on their biomedical relevance and concentration levels in sweat, paving the way for innovative approaches to monitoring health through wearable devices.

3 Nanomaterials and manufacturing of wearable biosensors

3.1 Nanomaterials

3.1.1 Nanomaterials in wearable biosensors

Nanotechnology is poised to drive significant progress in the development of wearable biosensors for cardiovascular monitoring [69–71]. This technology primarily involves nanoparticles, which are materials where all three dimensions are at the nanoscale [72]. In comparison, nanotubes and nanowires have one dimension at the nanoscale, with nanowires being solid and nanotubes hollow in structure [26, 73–75]. For detecting the presence or absence of specific analytes or biomarkers, zero-dimensional (0D) nanostructures like gold nanoparticles are commonly used. In creating tools with enhanced sensitivity for quantitative biomarker detection, one-dimensional (1D), two-dimensional (2D), and three-dimensional (3D) nanomaterials are utilized. Electrochemical biosensors, in particular, often incorporate 1D and 2D materials such as carbon nanotubes (CNTs), gold nanowires

(Au NWs), and graphene due to their high conductivity and electrical conductance properties. Metal-organic frameworks and their derivatives represent a focus area in the development of 3D nanomaterial-based wearable sensors, showcasing the breadth of research in this field [76–78].

Figure 2a categorizes nanomaterials by their dimensions [79]. Nanoparticles have uniform nanoscale dimensions and minimal difference between their longest and shortest axes. Conversely, 1D materials have one nanoscale dimension and vary between solid and hollow structures, such as nanowires and nanotubes, respectively. Zhang et al. developed a polyvinylpyrrolidone (PVP) hydrogel with cross-linking to enable analyte-induced reactions (Fig. 2b) [80], showcasing a method for quick and sensitive detection visible to the naked eye, allowing for rapid quantitative analysis.

Gold is especially favored in wearable electronics for its outstanding electrical conductivity, mechanical strength, stability, biocompatibility, and the availability of wet chemistry synthesis methods that allow for precise control over nanostructures. Among gold nanostructures, gold nanoparticles (AuNPs), gold nanowires (AuNWs), gold nanotubes (AuNTs), and gold nanosheets (AuNSs) are particularly valued for their stretchability, enhancing their application in soft electronic devices (Fig. 2c) [81].

3.1.2 Strategy of nanomaterial synthesis

The synthesis of nanoparticles (NPs) encompasses diverse methodologies, broadly categorized into top-down and bottom-up approaches [79, 82]. The top-down method involves mechanically breaking down solid materials into smaller particles, while the bottom-up approach focuses on creating NPs from metal salts or the decomposition of metal precursors in solvents, offering superior control over particle size. The bottom-up technique, preferred for its precision in particle size management, involves processes like reduction, sonolytic, photolytic, or thermal decomposition [83, 84].

The synthesis of CNTs, a significant milestone in nanotechnology, is facilitated through various methods, enabling their widespread applications [20, 31, 73]. The three main techniques for CNT synthesis include arc discharge, laser ablation, and chemical vapor deposition (CVD). Among these, CVD stands out for its efficiency, utilizing a suitable catalyst and carbon source to produce CNTs. A widely adopted method for synthesizing CNT fibers employs wet spinning, wherein nascent CNTs, dissolved or dispersed in a liquid medium, are extruded through a nozzle and subsequently solidified into a fiber via the removal of the dispersant, rendering this approach conducive for scaled production. Through the spinning of CNT

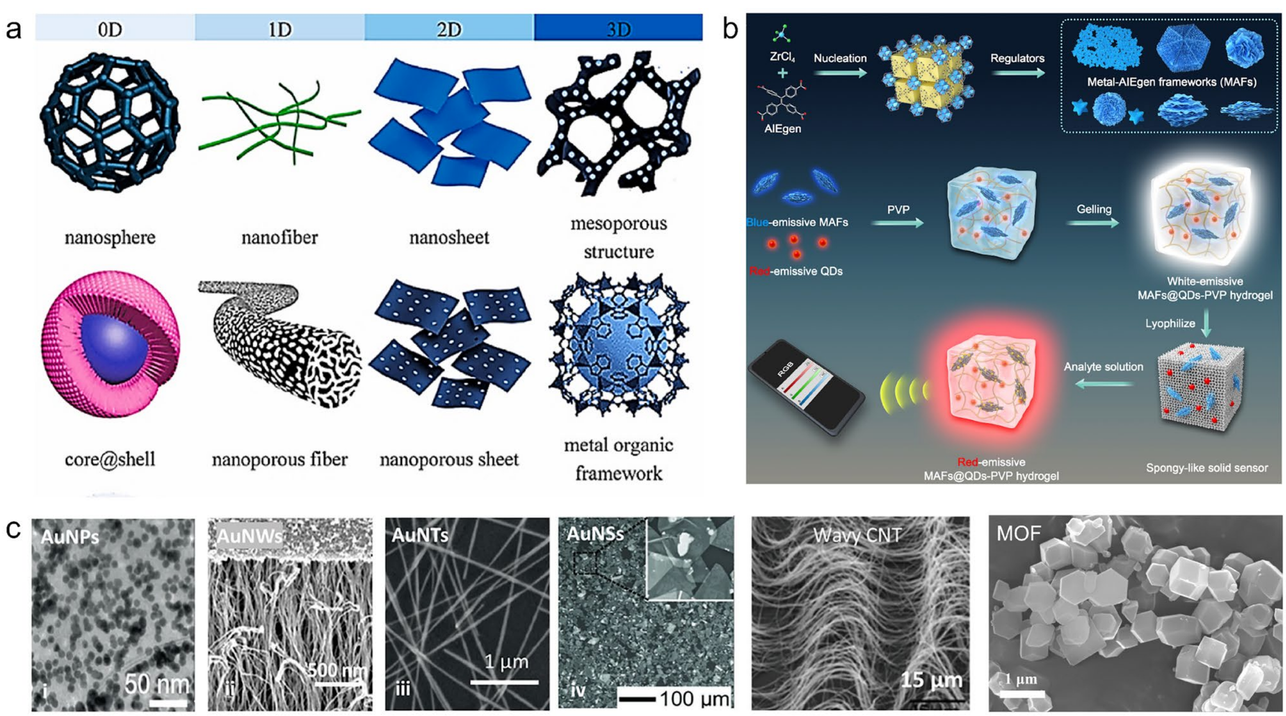

Fig. 2 Representative nanomaterials used in wearable biosensors. **a** Classification of 0D, 1D, 2D, and 3D nanostructures [79]. Copyright 2022, Elsevier. **b** Generation of various metal-AIEgen frameworks (MAFs) and construction of MAFs@quantum dots-polyvinylpyrrolidone (QDs-PVP) hydrogel composite, accompanied by a digital sensing approach. Reproduced with permission [80]. Copyright 2022, AAAS. **c** Different nanomaterials including gold nanoparticles (AuNPs), gold nanowires (AuNWs), gold nanotubes (AuNTs), gold nanosheets (AuNSs), wavy carbon nanotubes (CNTs), and metal-organic frameworks (MOFs). Reproduced with permission [81]. Copyright 2021, Wiley-VCH

socks, flexible ropes of specified dimensions can be directly attained, facilitating facile charge mobility and exhibiting exemplary electrical and thermal transfer properties, critical for efficient electron conversion from active materials to current carriers. In addition, one research employed CNTs to enhance carrier mobility and reduce frequency dispersion [85]. The interaction between PVA and CNTs generates longer interfacial polarization electric fields, improving the positive permittivity response.

The inception of graphene extraction witnessed a mechanical exfoliation of graphite utilizing adhesive tape, a method which, while yielding premium graphene sheets pivotal for foundational investigations, is not congruent with the production requisites of larger quantities for expansive applications [28, 29, 56, 86]. Subsequent advancements have heralded a spectrum of techniques for the generation of single or few-layer graphene sheets, spanning from CVD to chemical methodologies encompassing the oxidation and reduction of graphite, and extending to mechanical exfoliation via ball milling. Among these, CVD emerges as particularly efficacious in producing large-area graphene sheets with minimal structural aberrations. Nonetheless, a salient challenge intrinsic to the CVD process resides in the transfer of graphene from the metallic substrate to the designated target substrate, while preserving its qualitative integrity. In contrast, the transformation of natural graphite to GO, and its subsequent reduction to reduced GO (rGO), yields a product punctuated with imperfections. Despite inherent limitations, the economically viable rGO features enhanced binding propensities attributed to functional groups, albeit with defects that mitigate its electron conductivity and cycling capacity. Owing to its formidable electrical and electrochemical properties, both intrinsic and functionalized, graphene has been adroitly integrated into a plethora of sensor modalities, from mechanical to electrochemical.

The synthesis of MOFs involves various methods and parameters including temperature, reaction time, pressure, pH, and solvent choice [18–20, 81]. These synthetic approaches are pivotal in determining the resulting MOF structures and features. Key methods include slow diffusion, hydrothermal (solvothermal) synthesis, electrochemical, mechanochemical, microwave-assisted heating, and ultrasound techniques, each with its specific advantages in MOF production. Slow diffusion involves gradual interaction of species through methods like solvent liquid diffusion, where two layers of different density interact at an interface, facilitating crystal growth. Hydrothermal (solvothermal) synthesis uses the self-assembly of products from soluble precursors within a sealed space (autoclave) under autogenous pressure, typically at temperatures ranging from 80 to 260 °C. This method, initially used in zeolite synthesis, has been adapted for MOFs, often requiring long reaction periods. Microwave-assisted synthesis heats solutions with microwaves to rapidly produce nanosized metal crystals, although not commonly used for crystalline MOFs, it allows for high-speed synthesis and control over particle shape and size. Mechanochemical synthesis involves physical grinding to induce reactions without solvents, offering an eco-friendly alternative. Electrochemical synthesis provides precise control over MOF formation by applying electrical currents. Each of these methods offers unique advantages for MOF synthesis, affecting the crystallinity, purity, and physical properties of the final product. The choice of synthesis method is crucial for tailoring MOF characteristics for specific applications, highlighting the importance of understanding and optimizing these synthetic approaches.

3.2 Manufacturing

The process of manufacturing wearable sensors involves intricate methods to achieve the desired sensitivity and functionality. One notable example is the creation of a polydimethylsiloxane (PDMS) sensor film, which features dome-like pyramids and intersecting supportive walls (Fig. 3a). This structure was produced using a bifurcated molding method [87]. After applying a gold sputtering technique, a conductive Au-PDMS sensor film emerged. The assembly of the sensor required the precise alignment of two pieces of this conductive film in a face-to-face manner. The sensor's complex microstructure significantly enhances its sensitivity across a wide pressure range. However, modifying the microstructure in the resistive sensing layer to increase sensitivity can introduce several drawbacks [88].

Another manufacturing technique involves the development of graphene patterns on tape surfaces (Fig. 3b) [86]. Initially, a silicon mold with positive patterns, created from SU-8 photoresist, is prepared on a silicon wafer surface. This mold is then used in a soft lithography process to imprint negative patterns onto a PDMS substrate, where "negative" refers to channels or depressions on the PDMS surface. Next, aqueous suspensions of graphene nanoplatelets are spread over the PDMS surface. After drying on a hotplate, a thin graphene film covers the entire PDMS surface. Scotch tape is then applied and removed to strip away excess graphene from non-patterned areas. This step is repeated as necessary to remove all unwanted graphene, leaving behind the desired graphene within the PDMS's negative patterns due to its subsurface positioning. The final step involves transferring these graphene structures onto a target tape by applying and then peeling off the tape from the PDMS surface. The Sensor Transfer process enables the application of microscale graphene patterns onto the final tape surface, showcasing a sophisticated method for fabricating sensitive and functional wearable sensors.

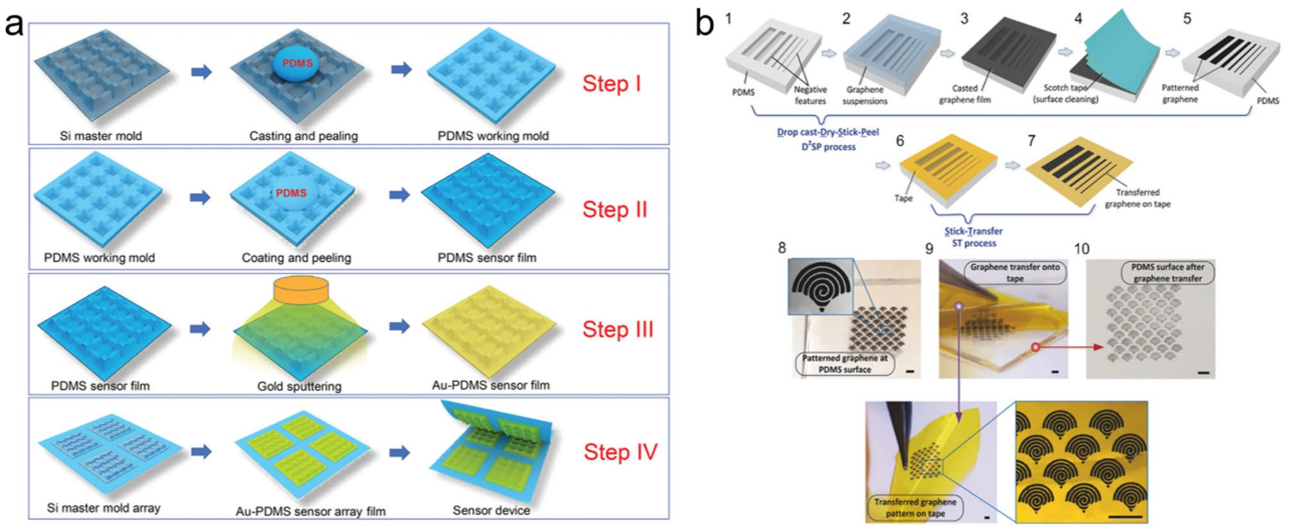

Fig. 3 Manufacturing processes for wearable biosensors using nanomaterials. **a** Diagrammatic representation of the construction of a resistive sensor. The illustration details the manufacturing methods of an ultra-sensitive pressure sensor. Step I involves creating the PDMS mold, Step II involves composing the PDMS film, Step III is related to forming the Au-PDMS sensor film, and Step IV pertains to the final assembly of the sensor. Reproduced with permission [87]. Copyright 2020, Wiley-VCH. **b** Illustrative depiction of the graphene patterning process on tape: (1) Using soft lithography to create inverse patterns on the PDMS substrate. (2) Covering the PDMS surface with graphene suspensions. (3) Forming a graphene film on the PDMS. (4) Using scotch tape to remove graphene outside the negative patterns. (5) Creating graphene patterns within the PDMS negative patterns. (6) Attaching a target tape to the PDMS. (7) Transferring graphene patterns to the selected tape. (8, 9) Displaying basic steps in graphene patterning and transfer through visual illustrations; scale bars are 1 mm. (10) Showing graphene patterns in PDMS structures, with 15.4 µm depth and 10.3 µm thickness, successfully transferred to polyimide tape. Reproduced with permission [86]. Copyright 2017, Wiley-VCH

4 Representative applications in cardiovascular monitoring

4.1 Electrocardiogram

The electrocardiogram (ECG) is a critical diagnostic tool widely used in medical practice, particularly by cardiologists [89–94]. It provides essential insights into cardiac health and broader health metrics, such as electrolyte imbalances or the effects of medication [95–97]. The development of wearable biosensors has enabled real-time monitoring of cardiac functions, greatly advancing cardiovascular care [98].

Nanomaterials have significantly improved the sensitivity and clarity of wearable biosensors for heart health monitoring [28, 99]. Traditional Ag/AgCl electrodes, although effective, often cause skin irritation and suffer from poor adherence due to their rigidity [15, 100]. This has led to the exploration of flexible dry electrodes made from materials like silver nanowires (AgNWs), graphene, and conductive polymers, designed for flexibility, breathability, and signal clarity [101, 102]. These innovations aim to preserve the accuracy of ECG monitoring by ensuring electrodes conform comfortably to the skin, reducing external disturbances, and ensuring consistent signal capture. The pursuit of ultra-low impedance electrodes minimizes signal disruption from external noise, enhancing the accuracy of cardiovascular monitoring [103].

Nanomaterials like graphene, carbon nanotubes (CNTs), and nanocomposites have been extensively researched for their application in ECG monitoring. Graphene, for instance, is known for its high electrical conductivity and flexibility, which enhances the signal-to-noise ratio (SNR) and allows for the development of wearable ECG sensors that can conform to the skin's surface for improved signal acquisition [104–106]. However, these advanced biosensors are often more complex and costly to produce, potentially limiting widespread accessibility. Smartwatches, on the other hand, represent a more consumer-friendly option, offering convenience and the ability to perform a variety of functions beyond ECG monitoring. While smartwatches have made significant strides in ECG technology, incorporating dry electrodes for non-invasive monitoring, they may lack the same level of sensitivity and specificity found in dedicated nanomaterial biosensors [107]. This difference can lead to variations in accuracy, especially in the detection of subtle cardiac anomalies. The form factor of smartwatches may not always ensure optimal electrode placement as well which could affect the quality of the ECG readings. Despite these differences, both technologies play vital roles in monitoring cardiovascular health monitoring. Smartwatches offer an entry point for everyday users to engage with their heart health, while nanomaterial biosensors provide a more advanced tool for clinical settings or detailed health analysis. Integrating these advanced materials and designs into device systems poses a challenge but is essential for developing next-generation wearable biosensors [108].

Machine learning plays a transformative role in analyzing real-time ECG data from nanomaterials-based sensors [96, 109, 110]. Modern AI techniques, such as deep-learning convolutional neural networks (CNNs), provide rapid ECG interpretations comparable to human analysts [111–113]. The combination of extensive ECG databases and clinical data has led to AI models capable of identifying conditions like left ventricular dysfunction, concealed atrial fibrillation, and hypertrophic cardiomyopathy, and predicting personal attributes such as age, gender, and ethnicity [114, 115]. As wearable ECG technology becomes more prevalent, the importance of AI interpretations grows [116], promising a new era of proactive health management.

Traditional diagnostic methods, including blood pressure evaluations and imaging techniques, while effective, have limitations [117, 118]. For instance, the intermittent measurements provided by blood pressure cuffs offer incomplete information, potentially comprising comprehensive cardiovascular care [119, 120]. The ECG, which records the heart's electrical activity through skin-affixed electrodes, typically involves a 12-lead setup with 10 electrodes for thorough diagnostics. However, simpler three-lead setups are also used (Fig. 4a) [121].

A novel approach combines ECG and photoplethysmography (PPG) sensors to measure pulse arrival time (PAT), aiding in continuous BP assessment. PAT measures the time difference between the heart's electrical activity (via ECG) and the peripheral pulse detected further along the arterial tree (via PPG), offering a non-invasive method for cardiovascular monitoring. This technique utilizes flexible, stretchable electronics, contrasting with traditional wired sensor arrays and marking a significant advancement in patient-centric care [122–125].

Visual illustrations of the device setup (Fig. 4b), as used by a 37-week-old patient in the pediatric intensive care unit (PICU), highlight the significant differences between this advanced system and the traditional, wired sensor array that is currently the standard of care [10, 12]. The color of each rectangle indicates specific channel connections, while different shades represent various types of electrodes. Patches 1

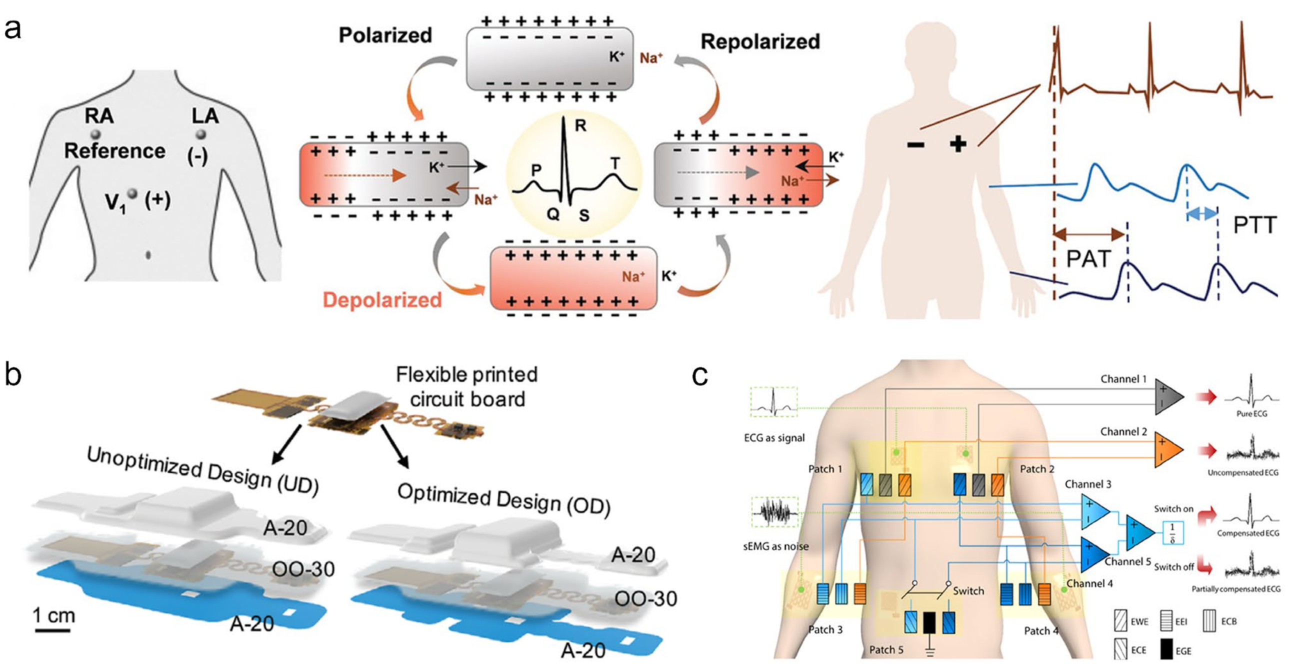

Fig. 4 Wearable biosensors for cardiovascular monitoring using ECG signals. **a** Modalities of electro-physiological mechanisms for observing cardiovascular vital signs. A tri-electrode bipolar framework designed for the acquisition of ECG data. The genesis and characteristics of the ECG signal. The extraction process of PAT is derived from ECG and PPG data. Reproduced with permission [126]. Copyright 2019, Elsevier. Reproduced with permission [121]. Copyright 2019, Springer Nature. **b** Soft, skin-attached devices designed for wireless blood pressure monitoring in pediatric intensive care unit (PICU) patients. An image presents a bird's-eye view of the devices. The system consists of a thoracic device equipped for ECG assessments and an extremity device enabled for PPG observations. Reproduced with permission [127]. Copyright 2021, Wiley-VCH. **c** Model for signal adjustment and experimental validation. Schematic of the circuit utilized in the validation experiment, with varied colors indicating channel connections and different shades symbolizing the roles of the electrodes. Reproduced with permission [128]. Copyright 2020, AAAS

and 2, each carrying three electrical wound electrodes (EWEs), were strategically placed on opposite sides of the chest, with a 10-cm gap between them, to record ECG data. In a different approach, Patches 3 and 4, which contain two surface electromyography (EMG) electrodes similar to those in the endocardial electrodes implant (EEI) and a singular epidermal control button (ECB), were affixed to the forearms to capture EMG data. Moreover, Patch 5, incorporating two epidermal control electrodes (ECE) and one epidermal ground electrode (EGE), was positioned on the lower right abdomen.

4.2 Pulse wave

The inception of a pulse wave is triggered by the heart's pumping action, which sends blood into both major and peripheral arteries during the ventricular systole phase, causing a rapid increase in blood pressure [56, 129]. This change in blood pressure originates from the heart and spreads through the arterial network, making pulse waves a valuable source of information about the cardiovascular system. Therefore, changes in the cardiovascular system can alter the pulse wave's amplitude, velocity, and other fundamental properties.

Analyzing arterial pulse waveforms is crucial for monitoring heart function, as it allows for the extraction of key cardiovascular indicators such as HR, BP, and PWV [130, 131]. These indicators are closely linked to early changes in the arteries, such as stiffness and endothelial dysfunction, making them essential for detecting various CVDs like arrhythmia, atherosclerosis, and coronary heart disease [132]. To enable continuous and unobtrusive monitoring, a range of wearable pulse sensors utilizing technologies like piezoelectric, resistive, capacitive, transistor-based pressure, and ultrasonic sensors have been developed [89, 132, 133]. These devices are gaining popularity due to their non-invasive nature and continuous monitoring capability. However, challenges such as reduced sensitivity, cost, wearability issues, and the need for external power sources limit their widespread use.

The introduction of nanomaterials in cardiovascular monitoring, particularly through wearable biosensors for pulse wave analysis, marks a significant advancement in non-invasive healthcare technologies [7]. Wearable pulse sensors developed with technologies like piezoelectric and capacitive sensors facilitate continuous, unobtrusive monitoring. They are increasingly vital for their non-invasive nature and their role in monitoring cardiovascular health during daily activities. Yet, their adoption is hindered by issues related to sensitivity, cost, and power requirements. Innovative approaches, such as textile biosensors that incorporate conductive yarns into clothing, are emerging [134]. These sensors can measure PWV, an accurate indicator of arterial stiffness and cardiovascular health, underscoring the potential of nanomaterials to improve the functionality and accessibility of cardiovascular monitoring tools. By integrating these advanced materials into wearable technologies, nanomaterials are setting the stage for sensitive, efficient, and patient-friendly cardiovascular health monitoring solutions, showcasing the transformative impact of nanotechnology in medical diagnostics and personalized healthcare [135].

Figure 5a highlights wearable biosensors as a key biotechnological innovation in the tracking of pulse waves [7]. Placing a wearable biosensor on specific skin regions (refer to Fig. 5b) [7], such as the neck (corresponding to the carotid artery), arm (aligned with the brachial artery), wrist (associated with the radial artery), finger (related to the coronary artery), and ankle (on the posterior tibial artery), allows it to convert pulse activities into electrical signals, which are then represented as a pulse waveform. These sensors are particularly useful for monitoring cardiovascular health during physical activities. A textile biosensor, capable of covering a wide pressure range and offering various designs (ranging from 326 Pa to 326 kPa), demonstrated its ability to track arterial pulse waves in a healthy woman before continuously and after exercise, showing significant changes in heart rate and output voltage amplitude (Fig. 5c) [134]. This textile, made from a blend of Terylene, nylon yarns, and standard threads, was seamlessly integrated into clothing for non-invasive pulse wave monitoring (Fig. 5d) [135]. The use of textile biosensors for measuring pulse wave velocity (PWV) has been validated as a reliable indicator of cardiovascular health [136–138]. This is achieved by analyzing the time difference between pulse waveforms captured at two points—specifically, between sensors placed on the arm and ankle. This method calculates a PWV of 13.63 m/s. Additionally, a floral-configured wireless textile biosensor was developed for pulse wave monitoring, indicating its effectiveness, especially in elderly individuals with less elastic arteries, as shown by increased PWV and changes in waveform characteristics (Fig. 5d) [136–138].

4.3 Sweat biosensors

Recently, wearable biosensors for point-of-care (POC) applications have gained significant interest due to their ability to monitor health markers non-invasively and in real time [28, 139, 140]. These devices, often made with cutting-edge nanomaterials, can analyze biomolecules in sweat, offering a promising avenue for continuous health monitoring. The rise of electrochemical biosensors is noteworthy for their capacity to detect a wide range of health indicators, including microorganisms, hormones, and metabolites, without invasive procedures. The integration of microfluidics, which allows for analysis in tiny volumes, with compact and flexible designs has made these wearable technologies more user-friendly and practical [141–143]. However, there is

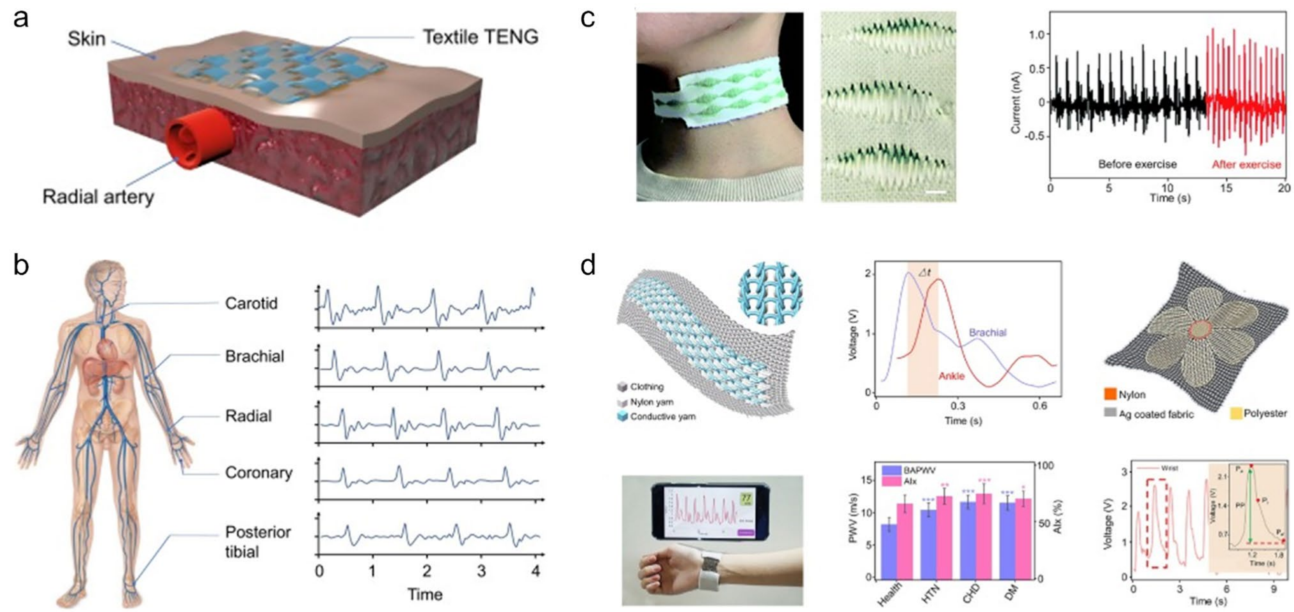

Fig. 5 Wearable biosensors for pulse wave monitoring. **a** A fabric-based wearable biosensor positioned over the radial artery to detect pulse wave activity. Reproduced with permission [7]. Copyright 2021, Cell Press. **b** Wearable biosensors are placed at different arterial locations for real-time tracking of pulse wave activity. Reproduced with permission [7]. Copyright 2021, Cell Press. **c** Wearable sensor for heart rate measurement. Images of a clothing-like triboelectric sensor featuring random stitch designs tailored for pulse wave tracking. Changes in the pulse waveform, detected by the apparel-integrated triboelectric sensor, before and after physical exertion. Reproduced with permission [134]. Copyright 2018, RSC. **d** Wearable biosensor for pulse wave velocity measurement. Diagrammatic representation of an all-textile triboelectric sensor grid. Live tracking of the pulse waveform at the wrist using an all-textile triboelectric sensor grid. A schematic representation of a wireless textile sensor, featuring a silver-coated fabric used as the foundational layer and electrode, overlaid by a textile with a raised floral design. Pulse waveforms were remotely recorded utilizing a textile sensor worn by a 75-year-old female. Reproduced with permission [135]. Copyright 2020, AAAS. Reproduced with permission [61]. Copyright 2020, Cell Press

still considerable potential for improvement in the accuracy and range of physiological data these devices can interpret. Advances in nanotechnology could further enhance the effectiveness of POC biosensors by incorporating new, more sensitive materials.

One breakthrough example is the Flexible Integrated Sweat Analyser (FISA), capable of assessing multiple sweat-based metabolites and electrolytes, as well as skin temperature, during extended physical activity (Fig. 6a) [144]. This device, built on a flexible polyethylene terephthalate [145] substrate, ensures a strong connection with the skin and uses flexible printed circuit board (fPCB) technology to integrate signal conditioning, processing, and wireless communication. It represents a significant step forward in multiplexed sensor technology for sweat analysis, with each electrode having a diameter of 3 mm (Fig. 6a).

The challenge of noninvasive glucose monitoring through sweat analysis has spurred the development of novel approaches. Traditional methods have faced obstacles such as inconsistent sweat production, variability in glucose oxidase activity due to the secretion of lactic acid and alterations in ambient temperature, and enzyme delamination attributable to mechanical friction and dermal deformation [146–148]. The introduction of a wearable device that not only monitors glucose in sweat but also administers medication through the skin in response to glucose levels demonstrates the potential for sophisticated, real-time health management (Fig. 6b) [149]. A meticulously engineered multilayer patch and the miniaturization of the sensor have significantly improved the efficiency of both sweat collection and the sensing process. The accuracy of glucose detection is further enhanced by using multiple modes of detection. Moreover, the compact design of the sensor not only makes it highly effective but also allows for its integration into a convenient, strip-like, disposable device.

Furthermore, a wearable patch developed by the Gao group showcases the ability to detect inflammation markers like CRP in perspiration, integrating methods to induce sweat, channel it for analysis, and measure relevant parameters for accurate CRP calibration (Fig. 6c) [150]. It combines iontophoretic perspiration induction, microfluidic pathways for sweat sampling, and reagent transport, with a graphene-incorporated sensor array for CRP measurement. The sensor uses an electrode equipped with anti-CRP antibodies attached to gold nanoparticles. It also assesses ionic strength, pH, and temperature to calibrate the CRP sensor

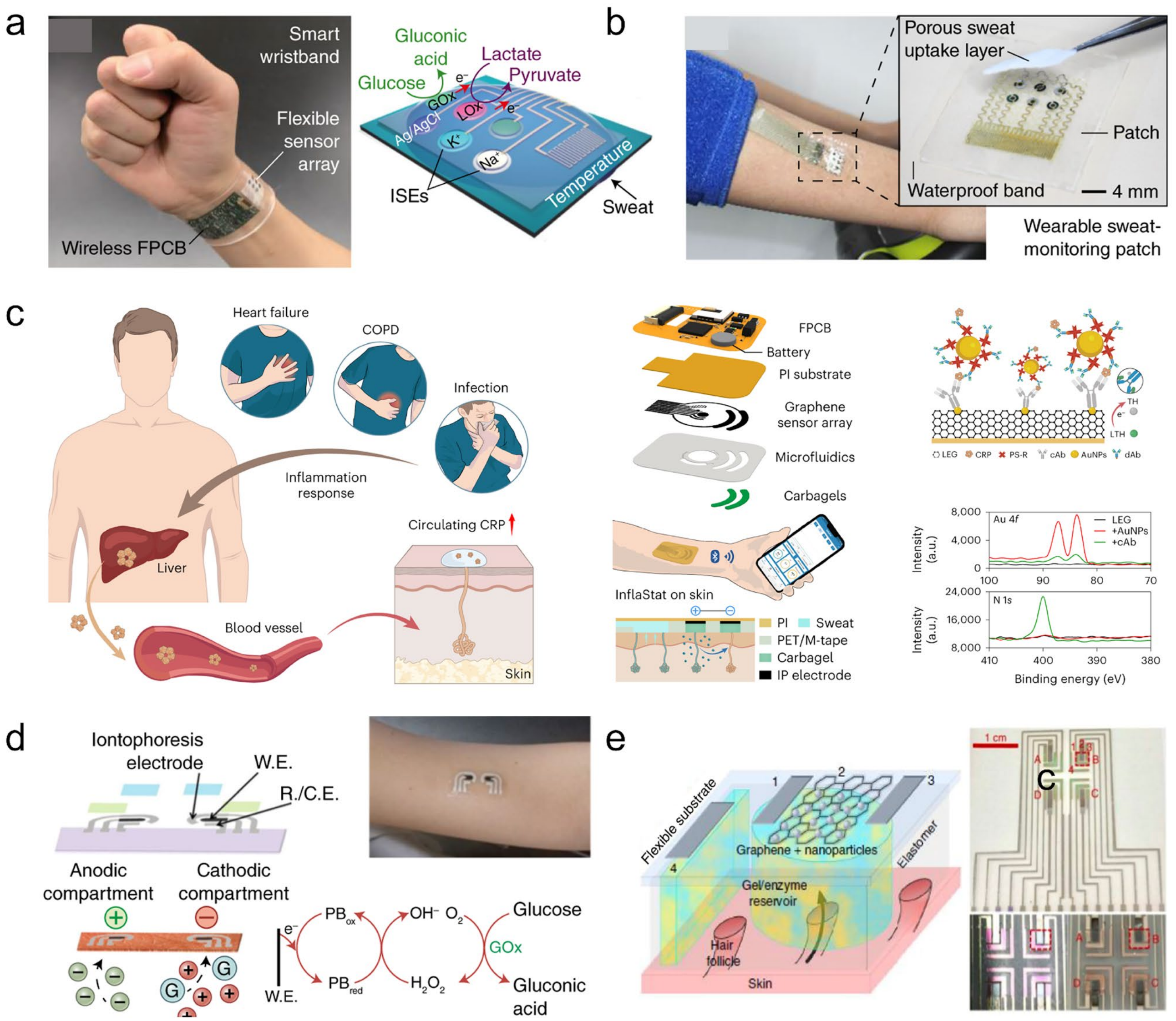

Fig. 6 Wearable biosensors for cardiovascular health monitoring. **a** The flexible integrated sensing array (FISA) performs comprehensive sweat analysis using a multi-sensor sensor array and a flexible, wireless printed circuit board, worn on the wrist. Included sensors: glucose, lactate, sodium, potassium, temperature. Reproduced with permission [144]. Copyright 2016, Springer Nature. **b** A patch for sweat-driven glucose monitoring/treatment, worn on the forearm, features a porous layer for sweat absorption and functions effectively with minimal sweat. Reproduced with permission [149]. Copyright 2016, AAAS. **c** A wearable biosensor provides non-invasive, wireless monitoring of inflammation by measuring sweat levels of CRP and additional metrics using an iontophoretic component, a microfluidic component, and a flexible light light-emitting graphene sensor array. Reproduced with permission [150]. Copyright 2023, Springer Nature. **d** A tattoo-style glucose sensor employs reverse iontophoresis, showcased with a device prototype adhered to the skin, demonstrating the utility of an interstitial fluid glucose sensor. Reproduced with permission [151]. Copyright 2015, ACS Publications. **e** Non-invasive glucose monitoring is achieved through a transcutaneous, path-selective iontophoretic approach using small, graphene-based pixel arrays, with four discrete extraction and detection spots. Reproduced with permission [152]. Copyright 2018, Springer Nature

in real time. In participants with chronic obstructive pulmonary disease (COPD), current or past infections, or heart failure, the elevated CRP levels detected by the patch correlate strongly with serum protein levels. Wearable biosensors that can instantaneously and sensitively detect inflammatory proteins in sweat could improve the management of chronic diseases [39].

In Fig. 6d, research from the Joseph Wang group introduces a nascent exploration of an entirely printed, transient tattoo-styled glucose sensor designed for non-invasive glucose monitoring [151]. This represents the first instance of a wearable, flexible epidermal diagnostic apparatus that combines reverse iontophoresis for extracting interstitial glucose and an enzyme-based amperometric biosensor. In vitro studies show the sensor's linear response to glucose concentrations within the physiological range, while effectively minimizing interference from commonly present electroactive substances. This initial study suggests that the tattoo-based iontophoresis-sensor method could streamline diabetes management and might be extended for non-invasive monitoring of additional analytes in the interstitial fluid that are of physiological importance. The system extracts glucose from the interstitial fluid using electroosmotic flow, moving through singular, optimal follicular routes in the skin made accessible through the sensor's pixel array (Fig. 6e) [152]. Continuous in vivo monitoring of interstitial fluid glucose using this pixel array accurately reflects blood sugar levels in healthy human participants, presenting a method that could allow for significant glucose monitoring in people with diabetes, eliminating the need for invasive finger-prick tests.

4.4 Bioimpedance

Bioimpedance (BI) operates by placing minimal current and voltage electrodes on the body, transmitting a slight alternating current through it. This process enables the estimation of body composition through bioimpedance measurement [153–157]. Deviations in voltage, or in some cases, radiofrequency signals, stemming from changes in blood volume and velocity within the thoracic cavity, are crucial for calculating parameters such as stroke volume and cardiac output [158]. Similarly, alterations in thoracic impedance provide information about lung fluid levels [159].

Conventional weighing scales often utilize bioimpedance to analyze body composition, but recent advancements have made it possible to incorporate this feature into wearable devices [160, 161]. Wearable vests that measure thoracic impedance have shown effectiveness in monitoring pulmonary fluid in patients with heart failure, potentially improving their clinical outcomes. Research on using such a vest for patients recovering from acute heart failure has demonstrated its algorithmic effectiveness in detecting subsequent heart failure episodes [162]. Bioimpedance is also used to measure PWV and estimate BP [129]. A wearable device attached to the wrist employs this technology with only minimal variations in blood pressure readings, in contrast to traditional devices [163].

However, the technology faces challenges, including movement perturbations, especially among ambulatory patients, and the positioning of electrodes, which can affect the signals. This necessitates careful consideration during the development of algorithms. Various factors, such as skin conditions, adhesive types, pregnancy, metallic implants, and physiognomy, may affect measurement accuracy [163]. The efficacy of this method across different practical scenarios remains a topic of exploration, with existing data showing mixed results. Despite the availability of traditional BP monitoring devices, they are often seen as intrusive and burdensome.

An electrical bioimpedance-based wearable BP monitoring system introduces a novel approach, using ultra-thin, self-adhering, lightweight graphene electronic tattoos as the interface between the device and the skin [164–166]. This system can monitor arterial BP for periods exceeding 300 min, a significant improvement over previous durations, with the graphene tattoos providing BP data accurately within industry standards.

Bioimpedance readings (Bio-Z) allow for deep tissue sensing due to the significant penetration depth of electrical currents, enabling effective monitoring of hemodynamic parameters directly from arteries. Graphene electronic tattoos (GETs), being self-adhering and having minimal impedance, maintain a stable position on the skin, ensuring consistent sensing over extended periods. The graphene-integrated BP (Z-BP) solution outlined here shows durability against electrode displacements and sensor movement. These unique GETs allow for extended BP monitoring (beyond 5 h, a substantial advancement from previous studies) during various activities, with the measurements demonstrating remarkable accuracy. The proposed Z-BP system represents a significant step forward in improving wearable BP monitoring methods.

4.5 Ultrasound

Recently, there has been a significant surge of interest in the area of flexible acoustic bioelectronics, with a particular focus on flexible ultrasound bioelectronics [167, 168]. This burgeoning field is witnessing innovative developments, including an adhesive ultrasound device designed for prolonged, continuous imaging of various organs, and a uniquely stretchable ultrasound device optimized for cardiac imaging. These inventions symbolize two divergent evolutionary trajectories within the sector.

Wearable ultrasound technologies have seen remarkable innovation, particularly in the development of miniaturized, flexible systems that can be directly integrated into wearable devices for continuous monitoring. These systems leverage cutting-edge materials and fabrication techniques to achieve high-resolution imaging capabilities while maintaining flexibility and comfort for the user. One notable breakthrough involves the use of liquid metal transducers, which offer exceptional acoustical properties and can be embedded in elastic carriers, enabling the device to stretch and bend without compromising its functional integrity [124]. This development paves the way for real-time, on-the-go ultrasound imaging, offering unprecedented opportunities for monitoring vital organs and blood flow in a non-invasive manner. Furthermore, advances in AI and machine learning algorithms have enhanced the capability of these wearable devices to analyze ultrasound data in real time, providing immediate insights into the user's health status. This integration of smart analytics into wearable ultrasound devices represents a significant step forward in personalized healthcare, allowing for early detection of abnormalities and timely medical intervention.

The adhesive ultrasound device utilizes a compact, rigid ultrasound probe that is attached to the skin using a coupling agent. This agent is a durable, moisture-retaining, and biocompatible blend of hydrogel and elastomer, emphasizing adhesive strength over device flexibility [169, 170]. This rigid nature of this ultrasound probe enables high array density and exceptional image resolution. It is versatile enough to image a wide range of internal structures, such as the heart, muscles, and blood vessels, and maintains consistent image quality even during physiological movements. Demonstrating reliable performance, this device can be used for extended, continuous periods of up to 48 h.

Conversely, the inherently stretchable ultrasound imager embodies a modern design philosophy aimed at creating thin, adaptable biodevices that conform to the body's contours [168, 171]. Encapsulated in a triblock copolymer, this device features piezoelectric transducer arrays and electrodes made from a liquid metal composite. It boasts a low Young's modulus of 921 kPa and an impressive stretchability of approximately 110% [167]. When evaluating its imaging capabilities—including spatial and signal clarity, locational precision, dynamic range, and image contrast—as well as its effectiveness in echocardiography from various angles, movement tracking, and automated image analysis, this device offers a promising model for wearable ultrasound imaging. However, the use of inherently stretchable materials faces limitations due to concerns over their durability and reliability, suggesting they may not match the high-end performance of traditional, rigid probes [123, 172, 173]. Furthermore, the stretchable imager encounters such as reduced image clarity, variable image quality during movement, restricted continuous imaging durations, susceptibility to external interference, and a higher risk of device malfunction.

4.6 Phonocardiogram (PCG)

Cardiac auscultation, the practice of listening to heart sounds, is a quintessential diagnostic tool. It offers deep insights into the functioning heart valves, and blood flow patterns, and can reveal various cardiac issues such as arrhythmias, valve abnormalities, and heart failure [40, 174]. The phonocardiogram, which visually represents these sounds by charting time against amplitude, is crucial for early detection of cardiovascular diseases. The push towards smaller, more flexible heart sound sensors is significantly driven by advancements in micro-electromechanical systems (MEMS).

To overcome common issues like sensor malfunction due to motion or on hairy skin, the team led by Firat Güder developed an acoustic coupling module [7, 175]. They used a 3D-printed polylactic acid (PLA) mold to fabricate a water-silicone composite acoustic transducer. This device, combined with a conventional microphone and worn at the waist, outperforms traditional stethoscopes in heart sound detection.

In the domain of sensor flexibility, the Takao Someya team has engineered an ultra-sensitive mechanical acoustic sensor made entirely of nanofibers. This sensor stands out for its air permeability, created using an electrospinning technique [176, 177]. It recorded signals demonstrate an exemplary signal-to-noise ratio.

Despite these advancements in creating flexible sensors for monitoring heart sound signals, challenges persist. Heart sounds are subtle and can be easily masked by background noise. Therefore, improving the sensitivity and noise resistance of these sensors is essential for future research.

5 Challenge and practice of wearable biosensors in cardiovascular healthcare

The clinical application of wearable biosensors in cardiovascular healthcare faces challenges [145, 178]. Advances in microelectronics have aided device miniaturization, yet further improvements are essential for performance enhancement and user-centric design. Signal processing in user-friendly devices can vary, leading to potential inaccuracies, highlighting the need for digital education and training, especially in remote areas. The sensitivity of wearable systems is critical for accurate disease diagnosis, with materials like graphene enhancing biosensor effectiveness. Integration of nanomaterials with technologies like 5G, AI, and IoT promises revolutionary developments, though obstacles such as cost, biocompatibility, and standardization persist. Moreover, the rise of wearable technology introduces data privacy concerns, necessitating advanced cybersecurity measures and clear data management agreements to protect sensitive health information. Addressing these challenges is vital for the successful clinical deployment of wearable biosensors, offering comprehensive and continuous monitoring for cardiovascular health.

Advancements in signal capture, medical diagnosis, triage, and data retrieval have underscored the importance of collected data. However, the adoption, processing, and utilization of these innovative technologies come with their unique challenges (Fig. 7a) [178]. The area of AI-integrated ECG (AI-ECG) deployment is still evolving. This includes how patients interact with AI-ECG results, the integration of AI-ECG functionalities with digital health records, safeguarding patient data, and considerations related to costs and reimbursement (Fig. 7b) [145].

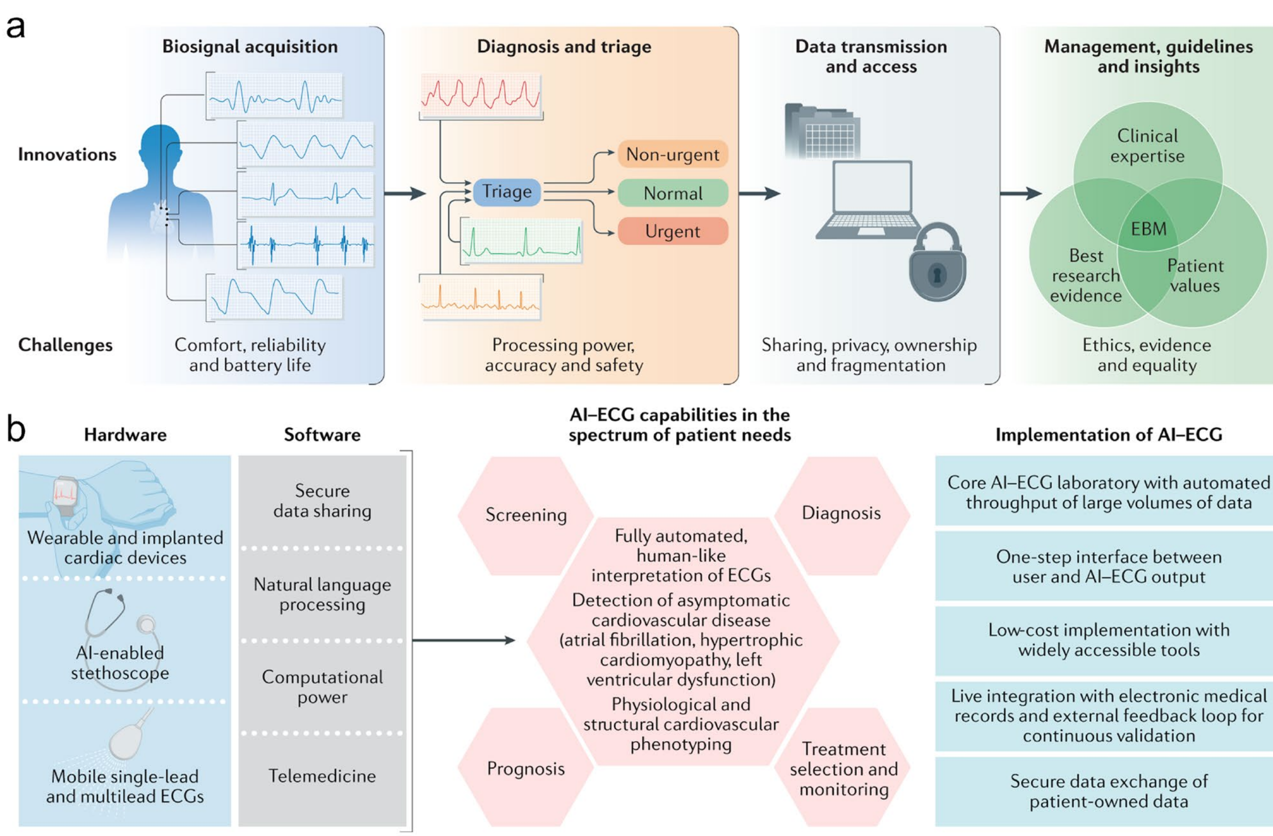

Fig. 7 Clinical applications of wearable biosensors in cardiovascular healthcare. **a** Emerging frameworks for cardiac monitoring using wearable devices. Reproduced with permission [178]. Copyright 2021, Springer Nature. **b** Framework for integrating AI-ECG analysis in clinical settings. Reproduced with permission [122]. Copyright 2021, Springer Nature

5.1 Risk assessment and lifestyle interventions

Traditional methods for assessing global cardiovascular disease risk have focused on clinical scores that project a 10-year risk [179–181]. However, these scores often fail to reflect the continuous changes in an individual's risk, which are influenced by daily habits. Despite the challenges of incorporating lifestyle choices into these assessments, wearable technology offers a new approach. It allows for a more detailed, dynamic, and accurate assessment of cardiovascular risk over an individual's lifetime [182–184]. Research has shown a negative correlation between physical activity, measured by wearables, and overall mortality. Activities of moderate to high intensity have been found to provide significant benefits in reducing mortality risk, as demonstrated in various American and Swedish studies.

5.2 Screening and diagnosis

Hypertension is a major health concern, leading to recommendations for early screening to prevent cardiovascular complications [185, 186]. Wearable devices, especially those worn on the wrist that can measure BP, offer a convenient alternative to conventional arm BP devices for everyday use. These devices could be key in detecting hypertension, facilitating BP self-monitoring, and adjusting antihypertensive medication dosages. However, it is crucial to conduct specific studies to validate the effectiveness of wrist-worn devices in these contexts [186, 187]. The development of sensors for continuous BP monitoring could allow for BP evaluation during sleep or physical activities, where traditional methods are not practical. This continuous monitoring could help detect conditions like cardiac arrest or significant BP drops, potentially enabling timely interventions.

5.3 Heart failure

For those managing heart failure [49], wearable devices can provide essential insights by tracking metrics such as physical activity, heart rate, recovery rate, and heart rate variability (HRV) [188–190]. For example, the stress test (a 6-min walk) quantified through a step tracker can reveal the severity of HF and associated mortality risk. HRV data can help identify individuals with mild symptoms who may not benefit significantly from cardiac resynchronization therapy. This makes wearables that monitor HRV vital in predicting patient responses to treatments. Additionally, emerging biomechanical sensors, like dielectric sensors, show promise in guiding HF treatments but require thorough testing and validation before clinical integration.

6 Challenges and outlooks

6.1 Portability

The comprehensive detection system, including wearable sensors, electrical circuits, and the battery, requires both easy transportability and a user-centric design [191, 192]. Although portability is crucial in cardiac monitoring, miniaturizing the device poses a significant challenge. Recent progress in microelectronics has led to smaller circuits, making it easier to develop small devices for heart monitoring. However, as technology advances, there are many opportunities to further refine and improve device designs to enhance performance, which need careful exploration.

6.2 Accessibility

Wearable devices for cardiac monitoring are noted not just for their small size but also for being user-friendly [182, 185, 193, 194]. However, signal processing in these devices faces several challenges. Differences in diagnostic results for heart conditions during various testing phases can confuse both medically trained and lay users, leading to potential inaccuracies. People with laboratory training are prone to mistakes, especially in ensuring test quality. Digital platforms could help educate the public about these accessible technologies. For disease diagnosis, providing thorough training based on established protocols, especially to healthcare workers in geographically remote areas, is essential.

6.3 Fidelity

Accurate diagnosing of cardiovascular diseases can be difficult when the signals are complex [195]. The sensitivity of wearable systems is key for testing. Disease signals often only slightly differ from those in healthy scenarios. Here, advanced materials like graphene or carbon nanotube-based electrochemical biosensors are valuable. Advances in nanotechnology have led to smaller, more effective wearable devices with better integration and interfacing capabilities.

6.4 Integration

Nanomaterials, along with technological advancements like 5G connectivity, AI, and the Internet of Things (IoT), have the potential to transform the development of portable, intelligent, and biocompatible devices [96, 182, 194, 196]. Wearable biosensors, like smartwatches and fitness bands, have become very popular for comprehensive health monitoring. Compared to current smartwatch technologies, nanomaterial biosensors offer better sensitivity, miniaturization, and the ability to monitor multiple parameters, but they also face challenges with cost, manufacturing complexity, biocompatibility, and standardization. These biosensors enable the use of advanced technologies, like the Internet of Medical Things (IoMT) for testing, AI for predictive analysis, faster testing methods, bioinformatic data exchange, and timely medical interventions. IoMT allows for efficient data gathering and analysis from biosensors, with AI and ML refining this data to improve the design and functionality of wearable biosensors continuously.

6.5 Data protection and management

The rise of wearable technology highlights three main concerns about data privacy in today's big data environment, where many entities seek access to large data sets to drive innovation [197, 198]. Protecting sensitive wearable data from potential breaches is critical. Anonymizing data by removing personal identifiers is one approach, but the potential use of metadata to re-identify users' needs consideration. Adopting advanced cybersecurity measures, like blockchain technology, may become crucial, especially as data breaches become more common with the ongoing transfer of data across platforms. With the large volumes of data generated by consumer wearables, setting clear expectations between users and healthcare providers is vital. New data agreements and electronic consents should clearly outline aspects such as how data is transmitted, how often it is reviewed, who has access to it, and how important data findings are communicated.

6.6 Artificial intelligence and machine learning

Machine learning, a dynamic segment of artificial intelligence, is gaining traction in the realm of cardiovascular healthcare [178]. It has demonstrated potential by identifying meaningful patterns within intricate datasets, such as diagnosing myocardial ischemia using cardiac CT scans and interpreting arrhythmias through wearable ECG devices. Furthermore, machine learning enables innovative communication methods between patients and healthcare professionals by leveraging automatic classification of biosensor data from various sources. This technology assesses the hemodynamic impacts of heart failure, arrhythmias, or coronary events, facilitating swift patient triage without the necessity for creating, testing, and implementing complex algorithms independently. However, machine learning is not without its challenges, including limitations due to data noise and training datasets that may not fully capture the nuances of clinical environments. For instance, one study highlighted that while a third of ECGs were not decipherable by consumer gadgets, expert analysis could classify them. Additionally, a pilot study showed that while data from a smartwatch-based PPG sensor, analyzed through a deep neural network, could accurately diagnose atrial fibrillation in stationary patients, it fell short of accuracy in patients who were moving.

Author contribution Xuxu Chen and Farid Manshaii wrote the main manuscript text. Karley Tioran, Xinhua Yin, Ming Yang, and Shaolei Wang prepared all the figures. Yunlei Zhou, Jie Zhao, Shichang Liu, and Kaidong Wang edited the main manuscript text. All authors reviewed the manuscript.

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Data availability No datasets were generated or analyzed during the current study.

Declarations

Competing interests The authors declare no competing interests.

References

1. Di Angelantonio E, Kaptoge S, Pennells L, De Bacquer D, Cooney MT, Kavousi M (2019) World Health Organization cardiovascular disease risk charts: revised models to estimate risk in 21 global regions. Lancet Global Health 7(10):E1332–E1345. https://doi.org/10.1016/S2214-109X(19)30318-3. (Who Cvd Risk Chart Working)
2. Mehra MR, Desai SS, Kuy S, Henry TD, Patel AN (2020) RETRACTION: cardiovascular disease, drug therapy, and mortality in Covid-19 (Retraction of Vol 382, art no E102, 2020). N Engl J Med 382(26):2582–2582. https://doi.org/10.1056/NEJMc2021225
3. Nowbar AN, Gitto M, Howard JP, Francis DP, Al-Lamee R (2019) Mortality from ischemic heart disease analysis of data from the World Health Organization and coronary artery disease risk factors from NCD risk factor collaboration. CIrculation-Carduivascular Qual Outcomes 12(6):e005375. https://doi.org/10.1161/CIRCOUTCOMES.118.005375
4. Pagidipati NJ, Gaziano TA (2013) Estimating deaths from Cardiovascular Disease: a review of global methodologies of Mortality Measurement. Circulation 127(6):749–756. https://doi.org/10.1161/CIRCULATIONAHA.112.128413
5. Reed GW, Rossi JE, Cannon CP (2017) Acute myocardial infarction. Lancet 389(10065):197–210. https://doi.org/10.1016/s0140-6736(16)30677-8
6. Schläpfer J, Wellens HJ (2017) Computer-interpreted electrocardiograms: benefits and limitations. J Am Coll Cardiol 70(9):1183–1192. https://doi.org/10.1016/j.jacc.2017.07.723
7. Lin J, Fu R, Zhong X, Yu P, Tan G, Li W, Ning C (2021) Wearable sensors and devices for real-time cardiovascular disease monitoring. Cell Rep Phys Sci 2(8). https://doi.org/10.1016/j.xcrp.2021.100541
8. Mizuno A, Changolkar S, Patel MS (2021) Wearable devices to monitor and reduce the risk of Cardiovascular Disease: evidence and opportunities. Annu Rev Med 72:459–471. https://doi.org/10.1146/annurev-med-050919-031534
9. Ahmad R, Wolfbeis OS, Hahn Y-B, Alshareef HN, Torsi L, Salama KN (2018) Deposition of nanomaterials: a crucial step in biosensor fabrication. Mater Today Commun 17:289–321. https://doi.org/10.1016/j.mtcomm.2018.09.024
10. Malhotra BD, Ali MA (2018) Nanomaterials in Biosensors: fundamentals and Applications. Nanomaterials Biosens 1–74. https://doi.org/10.1016/B978-0-323-44923-6.00001-7
11. Chen AC, Chatterjee S (2013) Nanomaterials based electrochemical sensors for biomedical applications. Chem Soc Rev 42(12):5425–5438. https://doi.org/10.1039/c3cs35518g
12. Maduraiveeran G, Sasidharan M, Ganesan V (2018) Electrochemical sensor and biosensor platforms based on advanced nanomaterials for biological and biomedical applications. Biosens Bioelectron 103:113–129. https://doi.org/10.1016/j.bios.2017.12.031
13. Li F (2023) Morphology controllable urchin-shaped bimetallic nickel-cobalt oxide/carbon composites with enhanced electromagnetic wave absorption performance. J Mater Sci Technol 148(0):250–259. https://www.jmst.org/EN/10.1016/j.jmst.2022.12.003
14. Shetty DK, Rodrigues LLR, Shetty AK, Nair G (2022) Machine learning based predictors of Cardiovascular Disease among Young adults. Eng Sci 17:292–302. https://doi.org/10.30919/es8d627
15. Bai Y, Yin L, Hou C, Zhou Y, Zhang F, Xu Z, Huang YA (2023) Response regulation for Epidermal Fabric Strain Sensors via Mechanical Strategy. Adv Funct Mater 33. https://doi.org/10.1002/adfm.202214119
16. Hasan MM, Hossain MM (2021) Nanomaterials-patterned flexible electrodes for wearable health monitoring: a review. J Mater Sci 56(27):14900–14942. https://doi.org/10.1007/s10853-021-06248-8
17. Li YY, Chen KR, Pang YS, Zhang JX, Wu M, Xu YR, Kong DS (2023) Multifunctional Microneedle patches via Direct Ink drawing of Nanocomposite inks for Personalized Transdermal Drug Delivery. ACS Nano 17(20):19925–19937. https://doi.org/10.1021/acsnano.3c04758
18. Qu YP, Zhou YL, Luo Y, Liu Y, Ding JF, Chen YL, Qi XS (2024) Universal paradigm of ternary metacomposites with tunable epsilon-negative and epsilon-near-zero response for perfect electromagnetic shielding. Rare Met 43(2):796–809. https://doi.org/10.1007/s12598-023-02510-x
19. Wang KD, Wu C, Wang F, Liao MH, Jiang GQ (2020) Bimetallic nanoparticles decorated hollow nanoporous carbon framework as nanozyme biosensor for highly sensitive electrochemical sensing of uric acid. Biosens Bioelectron 150:111869. https://doi.org/10.1016/j.bios.2019.111869
20. Wang KD, Wu C, Wang F, Liu CM, Yu CJ, Jiang GQ (2018) Situinsertion of carbon nanotubes into metal-organic frameworks-derived polyhedrons for highly sensitive electrochemical detection of Nitrite. Electrochim Acta 285:128–138. https://doi.org/10.1016/j.electacta.2018.07.228
21. Wang S, Cui Q, Abiri P, Roustaei M, Zhu E, Li Y-R, Hsiai TK (2023) A self-assembled implantable microtubular pacemaker for wireless cardiac electrotherapy. Sci Adv 9(42):eadj0540. https://doi.org/10.1126/sciadv.adj0540
22. Xiong WN, Feng H, Liwang HS, Li D, Yao WB, Duolikun D, Huang YA (2022) Multifunctional tactile feedbacks towards compliant Robot manipulations via 3D-Shaped electronic skin. IEEE Sens J 22(9):9046–9056. https://doi.org/10.1109/JSEN.2022.3162914
23. Yin J, Wang S, Di Carlo A, Chang A, Wan X, Xu J, Chen J (2023) Smart textiles for self-powered biomonitoring. Med-X 1(1):3. https://doi.org/10.1007/s44258-023-00001-3
24. Yu H, Gai M, Liu L, Chen F, Bian J, Huang Y (2023) Laser-induced direct graphene patterning: from formation mechanism

to flexible applications. Soft Sci 3(1):4. https://doi.org/10.20517/ss.2022.26
25. Zhou DZ, Dou BH, Kroh F, Wang CQ, Ouyang LL (2023) Biofabrication strategies with single-cell resolution: a review. Int J Extreme Manuf 5(4):042005. https://doi.org/10.1088/2631-7990/ace863
26. Zhou Y-L, Cheng W-N, Bai Y-Z, Hou C, Li K, Huang Y-A (2023) Rise of flexible high-temperature electronics. Rare Met 42(6):1773–1777. https://doi.org/10.1007/s12598-023-02298-w
27. Zhou Y, Lian H, Li Z, Yin L, Ji Q, Li K, Huang Y (2022) Crack engineering boosts the performance of flexible sensors. View 3(5):20220025. https://doi.org/10.1002/VIW.20220025
28. Zhou Y, Wang S, Yin J, Wang J, Manshaii F, Xiao X, Chen J (2024) Flexible metasurfaces for multifunctional interfaces. ACS Nano 18(4):2685–2707. https://doi.org/10.1021/acsnano.3c09310
29. Zhou Y, Yin L, Xiang S, Yu S, Johnson HM, Wang S, Chu PK (2024) Unleashing the potential of MXene-Based flexible materials for High-Performance Energy Storage Devices. Adv Sci 11(3):2304874. https://doi.org/10.1002/advs.202304874
30. Zhu H, Yao C, Wei BY, Xu CY, Huang XX, Liu Y, Li DC (2023) 3D printing of functional bioengineered constructs for neural regeneration: a review. Int J Extreme Manuf 5(4):042004. https://doi.org/10.1088/2631-7990/ace56c
31. Wang C, Zhang Z, Xu X, Wu H, Liu D, Meng S, Liu C (2023) Flexible and biocompatible Polystyrene/Multi-walled Carbon Nanotubes Films with High Permittivity and Low Loss. ES Mater Manuf 19:791. https://doi.org/10.30919/esmm5f791
32. Yuan R-m, Li H-j, Yin X-m, Lu J-h, Zhang L (2017) 3D CuO nanosheet wrapped nanofilm grown on Cu foil for high-performance non-enzymatic glucose biosensor electrode. Talanta 174:514–520. https://doi.org/10.1016/j.talanta.2017.06.030
33. Yuan X, Li C, Yin X, Yang Y, Ji B, Niu Y, Ren L (2023) Epidermal wearable biosensors for monitoring biomarkers of chronic disease in sweat. Biosensors 13(3)
34. Liu X, Peng H, Zhang T, Wang K, Dong Y, Wang K, Li J (2023) One-step brush-coating strategy for low-haze and water-resistant transparent wood films. Prog Org Coat 185:107912. https://doi.org/10.1016/j.porgcoat.2023.107912
35. Nelson BW, Low CA, Jacobson N, Areán P, Torous J, Allen NB (2020) Guidelines for wrist-worn consumer wearable assessment of heart rate in biobehavioral research. Npj Digit Med 3(1):90. https://doi.org/10.1038/s41746-020-0297-4
36. Tao Z, Zheng M, Li H, Yuan T, Peng H, Wang K, Li Y (2023) Photochromic transparent bamboo composite with excellent optical and thermal management for smart window applications. Ind Crops Prod
37. Vashistha R, Dangi AK, Kumar A, Chhabra D, Shukla P (2018) Futuristic biosensors for cardiac health care: an artificial intelligence approach. 3 Biotech 8(8):358. https://doi.org/10.1007/s13205-018-1368-y
38. Zhu P, Peng H, Rwei AY (2022) Flexible, wearable biosensors for digital health. Med Novel Technol Devices 14:100118. https://doi.org/10.1016/j.medntd.2022.100118
39. Zhang H, Gopinath SCB, Hu Y (2023) Spinal cord injury immunosensor: sensitive detection of S100β on interdigitated electrode sensor. Heliyon 9(9):e19304. https://doi.org/10.1016/j.heliyon.2023.e19304
40. Sharma P, Hui X, Zhou J, Conroy TB, Kan EC (2020) Wearable radio-frequency sensing of respiratory rate, respiratory volume, and heart rate. Npj Digit Med 3(1):98. https://doi.org/10.1038/s41746-020-0307-6
41. Xiao N, Yu W, Han X (2020) Wearable heart rate monitoring intelligent sports bracelet based on internet of things. Measurement 164:108102
42. Aladin AI, Whelton SP, Al-Mallah MH, Blaha MJ, Keteyian SJ, Juraschek SP, Michos ED (2014) Relation of resting heart rate to risk for all-cause mortality by gender after considering Exercise Capacity (the Henry Ford Exercise Testing Project). Am J Cardiol 114(11):1701–1706. https://doi.org/10.1016/j.amjcard.2014.08.042
43. Cooney MT, Vartiainen E, Laakitainen T, Juolevi A, Dudina A, Graham IM (2010) Elevated resting heart rate is an independent risk factor for cardiovascular disease in healthy men and women. Am Heart J 159(4):612–U134. https://doi.org/10.1016/j.ahj.2009.12.029
44. Xhyheri B, Manfrini O, Mazzolini M, Pizzi C, Bugiardini R (2012) Heart rate variability today. Prog Cardiovasc Dis 55(3):321–331. https://doi.org/10.1016/j.pcad.2012.09.001
45. Eppinga RN, Hagemeijer Y, Burgess S, Hinds DA, Stefansson K, Gudbjartsson DF, van der Harst P (2016) Identification of genomic loci associated with resting heart rate and shared genetic predictors with all-cause mortality. Nat Genet 48(12):1557–1563. https://doi.org/10.1038/ng.3708
46. Gong S, Yap LW, Zhang Y, He J, Yin J, Marzbanrad F&, Cheng W (2022) A gold nanowire-integrated soft wearable system for dynamic continuous non-invasive cardiac monitoring. Biosens Bioelectron 205:114072. https://doi.org/10.1016/j.bios.2022.114072
47. Su Y, Chen C, Pan H, Yang Y, Chen G, Zhao X, Chen J (2021) Muscle fibers inspired high-performance piezoelectric textiles for wearable physiological monitoring. Adv Funct Mater 31(19):2010962. https://doi.org/10.1002/adfm.202010962
48. Tu J, Torrente-Rodríguez RM, Wang M, Gao W (2020) The era of Digital Health: a review of Portable and Wearable Affinity biosensors. Adv Funct Mater 30(29):1906713. https://doi.org/10.1002/adfm.201906713
49. Ehret GB, Munroe PB, Rice KM, Bochud M, Johnson AD, Chasman DI (2011) Genetic variants in novel pathways influence blood pressure and cardiovascular disease risk. Nature 478(7367):103–109. https://doi.org/10.1038/nature10405
50. Flint AC, Conell C, Ren X, Banki NM, Chan SL, Rao VA, Bhatt DL (2019) Effect of systolic and diastolic blood pressure on Cardiovascular outcomes. N Engl J Med 381(3):243–251. https://doi.org/10.1056/NEJMoa1803180
51. Ribeiro F (2021) Resistance exercise for the management of arterial hypertension: an intervention that works! J Clin Hypertens 23(5):987–989. https://doi.org/10.1111/jch.14197
52. Kim J, Chou EF, Le J, Wong S, Chu M, Khine M (2019) Soft wearable pressure sensors for beat-to-beat blood pressure monitoring. Adv Healthc Mater 8(13):e1900109. https://doi.org/10.1002/adhm.201900109
53. Yi Z, Liu Z, Li W, Ruan T, Chen X, Liu J, Zhang W (2022) Piezoelectric Dynamics of Arterial Pulse for wearable continuous blood pressure monitoring. Adv Mater 34(16):2110291. https://doi.org/10.1002/adma.202110291
54. Kim HL, Kim SH (2019) Pulse Wave Velocity in Atherosclerosis. Front Cardiovasc Med 6:41. https://doi.org/10.3389/fcvm.2019.00041
55. Pereira T, Correia C, Cardoso J (2015) Novel methods for pulse Wave Velocity Measurement. J Med Biol Eng 35(5):555–565. https://doi.org/10.1007/s40846-015-0086-8
56. Yang T, Jiang X, Zhong Y, Zhao X, Lin S, Li J, Zhu H (2017) A wearable and highly sensitive graphene strain sensor for Precise Home-based pulse Wave Monitoring. ACS Sens 2(7):967–974. https://doi.org/10.1021/acssensors.7b00230
57. Heffernan KS, Stoner L, London AS, Augustine JA, Lefferts WK (2023) Estimated pulse wave velocity as a measure of vascular aging. PLoS ONE 18(1):e0280896. https://doi.org/10.1371/journal.pone.0280896
58. Bariya M, Nyein HYY, Javey A (2018) Wearable sweat sensors. Nat Electron 1(3):160–171. https://doi.org/10.1038/s41928-018-0043-y

59. Liu C, Xu T, Wang D, Zhang X (2020) The role of sampling in wearable sweat sensors. Talanta 212:120801. https://doi.org/10.1016/j.talanta.2020.120801
60. Zhong B, Jiang K, Wang L, Shen G (2022) Wearable sweat loss measuring devices: from the role of sweat loss to advanced mechanisms and designs. Adv Sci 9(1):2103257. https://doi.org/10.1002/advs.202103257
61. Meng KY, Zhao SL, Zhou YH, Wu YF, Zhang SL, He Q, Chen J (2020) A Wireless Textile-based Sensor System for Self-Powered Personalized Health Care. Matter 2(4):896–907. https://doi.org/10.1016/j.matt.2019.12.025
62. Kim J, Imani S, de Araujo WR, Warchall J, Valdés-Ramírez G, Paixão TRLC, Wang J (2015) Wearable salivary uric acid mouthguard biosensor with integrated wireless electronics. Biosens Bioelectron 74:1061–1068. https://doi.org/10.1016/j.bios.2015.07.039
63. Kaya T, Liu G, Ho J, Yelamarthi K, Miller K, Edwards J, Stannard A (2019) Wearable sweat sensors: background and current trends. Electroanalysis 31(3):411–421. https://doi.org/10.1002/elan.201800677
64. Van Hoovels K, Xuan X, Cuartero M, Gijssel M, Swarén M, Crespo GA (2021) Can wearable sweat lactate sensors contribute to sports Physiology? ACS Sens 6(10):3496–3508. https://doi.org/10.1021/acssensors.1c01403
65. Brothers MC, DeBrosse M, Grigsby CC, Naik RR, Hussain SM, Heikenfeld J, Kim SS (2019) Achievements and challenges for Real-Time sensing of Analytes in sweat within Wearable platforms. Accouunts Chem Res 52(2):297–306. https://doi.org/10.1021/acs.accounts.8b00555
66. Sonner Z, Wilder E, Gaillard T, Kasting G, Heikenfeld J (2017) Integrated sudomotor axon reflex sweat stimulation for continuous sweat analyte analysis with individuals at rest. Lab Chip 17(15):2550–2560. https://doi.org/10.1039/C7LC00364A
67. Lee YY, Sriram B, Wang SF, Kogularasu S, Chang-Chien GP (2024) Advanced nanomaterial-based biosensors for N-terminal pro-brain natriuretic peptide biomarker detection: progress and future challenges in cardiovascular disease diagnostics. Nanomaterials 14(2):153. https://doi.org/10.3390/nano14020153
68. Alawieh H, El Chemaly T, Alam S, Khraiche M (2019) Towards Point-of-Care Heart failure Diagnostic platforms: BNP and NT-proBNP biosensors. Sensors 19(22):5003. https://doi.org/10.3390/s19225003
69. Lu SM, Yu T, Wang YM, Liang LG, Chen Y, Xu F, Wang SQ (2017) Nanomaterial-based biosensors for measurement of lipids and lipoproteins towards point-of-care of cardiovascular disease. Analysta 142(18):3309–3321. https://doi.org/10.1039/c7an00847c
70. Tang LC, Yang JY, Wang YX, Deng RJ (2023) Recent advances in Cardiovascular Disease biosensors and Monitoring technologies. ACS Sens 8(3):956–973. https://doi.org/10.1021/acssensors.2c02311
71. Verma D, Singh KRB, Yadav AK, Nayak V, Singh J, Solanki PR, Singh RP (2022) Internet of things (IoT) in nano-integrated wearable biosensor devices for healthcare applications. Biosens Bioelectronics: X 11:100153. https://doi.org/10.1016/j.biosx.2022.100153
72. Jin H, Huynh TP, Haick H (2016) Self-healable sensors based nanoparticles for detecting physiological markers via skin and breath: toward Disease Prevention via Wearable devices. Nano Lett 16(7):4194–4202. https://doi.org/10.1021/acs.nanolett.6b01066
73. Lv T, Yao Y, Li N, Chen T (2016) Wearable fiber-shaped energy conversion and storage devices based on aligned carbon nanotubes. Nano Today 11(5):644–660. https://doi.org/10.1016/j.nantod.2016.08.010
74. Zhou YL, Cao ST, Wang J, Zhu HY, Wang JC, Yang SN, Kong DS (2018) Bright Stretchable Electroluminescent devices based on silver nanowire electrodes and High-k Thermoplastic elastomers. ACS Appl Nano Mater 10(51):44760–44767. https://doi.org/10.1021/acsami.8b17423
75. Zhou YL, Zhao CS, Wang JC, Li YZ, Li CX, Zhu HY, Kong DS (2019) Stretchable high-permittivity nanocomposites for epidermal alternating-current Electroluminescent displays. ACS Mater Lett 1(5):511–. https://doi.org/10.1021/acsmaterialslett.9b00376
76. Moghadam BH, Hasanzadeh M, Simchi A (2020) Self-powered wearable Piezoelectric sensors based on Polymer Nanofiber-Metal-Organic Framework Nanoparticle composites for arterial pulse monitoring. ACS Appl Nano Mater 3(9):8742–8752. https://doi.org/10.1021/acsanm.0c01551
77. Pal S, Su YZ, Chen YW, Yu CH, Kung CW, Yu SS (2022) 3D Printing of Metal-Organic Framework-based ionogels: wearable sensors with colorimetric and mechanical responses. ACS Appl Nano Mater Lett 14(24):28247–28257. https://doi.org/10.1021/acsami.2c02690
78. Wang K, Wu C, Wang F, Jiang G (2018) MOF-Derived CoPx nanoparticles embedded in Nitrogen-Doped Porous Carbon polyhedrons for Nanomolar Sensing of p-Nitrophenol. ACS Appl Nano Mater 1(10):5843–5853. https://doi.org/10.1021/acsanm.8b01501
79. Byakodi M, Shrikrishna NS, Sharma R, Bhansali S, Mishra Y, Kaushik A, Gandhi S (2022) Emerging 0D, 1D, 2D, and 3D nanostructures for efficient point-of-care biosensing. Biosens Bioelectronics: X 12:100284–100284. https://doi.org/10.1016/j.biosx.2022.100284
80. Zhang JJ, Li Y, CJiang XY (2022) Ultrasensitive point-of-care biochemical sensor based on metal-AIEgen frameworks. Sci Adv 8(30):eabo1874. https://doi.org/10.1126/sciadv.abo1874
81. Lyu QX, Gong S, Yin JL, Dyson JM, Cheng WL (2021) Soft wearable healthcare materials and devices. Adv Healthc Mater 10(17):2100577. https://doi.org/10.1002/adhm.202100577
82. Li HC, Song XK, Gong H, Tong LP, Zhou X, Wang ZY, Fan TX (2023) Prediction of Optical properties in Particulate Media using double optimization of dependent scattering and particle distribution. Nano Lett 24(1):287–294. https://doi.org/10.1021/acs.nanolett.3c03914
83. Chen Y, Yuchi Q, Li T, Yang G, Miao J, Huang C, Zhang L (2020) Precise engineering of ultra-thin Fe2O3 decorated Pt-based nanozymes via atomic layer deposition to switch off undesired activity for enhanced sensing performance. Sens Actuators B 305:127436. https://doi.org/10.1016/j.snb.2019.127436
84. Jiang B, Zhou K, Wang C, Sun Q, Yin G, Tai Z, Zhang L (2018) Label-free glucose biosensor based on enzymatic graphene oxide-functionalized tilted fiber grating. Sens Actuators B 254:1033–1039. https://doi.org/10.1016/j.snb.2017.07.109
85. Sun K, Wang C, Tian JH, Zhang Z, Zeng N, Yin R, Fan RH (2023) Magnetic-Driven Broadband Epsilon-Near-Zero materials at radio frequency. Adv Funct Mater. https://doi.org/10.1002/adfm.202306747
86. Oren S, Ceylon H, Schnable PS, Dong L (2017) High-resolution patterning and transferring of graphene-based nanomaterials onto tape toward roll-to-roll production of tape-based wearable sensors. Adv Mater Technol 2(12):1700223. https://doi.org/10.1002/admt.201700223
87. Li G, Chen D, Li C, Liu W, Liu H (2020) Engineered Microstructure Derived Hierarchical deformation of flexible pressure Sensor induces a supersensitive Piezoresistive Property in Broad Pressure Range. Adv Sci 7(18):2000154. https://doi.org/10.1002/advs.202000154
88. Zhao G, Qian F, Li X, Tang Y, Sheng Y, Li H, Chen T (2023) Constructing a continuous reduced graphene oxide network in

porous plant fiber sponge for highly compressible and sensitive piezoresistive sensors. Adv Compos Hybrid Mater 6(5):184. https://doi.org/10.1007/s42114-023-00754-w
89. Chu Y, Zhong JW, Liu HL, Ma Y, Liu N, Song Y, Lin LW (2018) Human pulse diagnosis for medical assessments using a wearable Piezoelectret Sensing System. Adv Funct Mater 28(40):1803413. https://doi.org/10.1002/adfm.201803413
90. Kim J, Banks A, Xie Z, Heo S, Gutruf P, Lee J, Rogers J (2015) Miniaturized flexible electronic systems with wireless power and near-field communication capabilities. Adv Funct Mater 25. https://doi.org/10.1002/adfm.201501590
91. Ramasamy S, Balan A (2018) Wearable sensors for ECG measurement: a review. Serson Reviwe 38(4):412–419. https://doi.org/10.1108/SR-06-2017-0110
92. Rapin M, Braun F, Adler A, Wacker J, Frerichs I, Vogt B, Chételat O (2019) Wearable sensors for frequency-multiplexed EIT and Multilead ECG Data Acquisition. IEEE Trans Biomed Eng 66(3):810–820. https://doi.org/10.1109/TBME.2018.2857199
93. Son D, Lee J, Qiao S, Ghaffari R, Kim J, Lee JE, Kim DH (2014) Multifunctional wearable devices for diagnosis and therapy of movement disorders. Nat Nanotechnol 9(5):397–404. https://doi.org/10.1038/NNANO.2014.38
94. Wang WC, Wang SH, Rastak R, Ochiai Y, Niu SM, Jiang YW, Bao ZN (2021) Strain-insensitive intrinsically stretchable transistors and circuits. Nat Electron 4(2):143–150. https://doi.org/10.1038/s41928-020-00525-1
95. Kwon JM, Jung MS, Kim KH, Jo YY, Shin JH, Cho YH, Oh BH (2021) Artificial intelligence for detecting electrolyte imbalance using electrocardiography. Ann Noninvasive Electrocardiol 26(3):e12839. https://doi.org/10.1111/anec.12839
96. Oresko JJ, Jin ZP, Cheng J, Huang SM, Sun YW, Duschl H, Cheng AC (2010) A wearable smartphone-based platform for Real-Time Cardiovascular Disease Detection Via Electrocardiogram Processing. IEEE Trans Inf Technol Biomed 14(3):734–740. https://doi.org/10.1109/TITB.2010.2047865
97. Yang Z, Zhou QH, Lei L, Zheng K, Xiang W (2016) An IoT-cloud based wearable ECG monitoring system for smart healthcare. J Med Syst 40(12):286. https://doi.org/10.1007/s10916-016-0644-9
98. Sivasankarapillai VS, Sharma TSK, Hwa K-Y, Wabaidur SM, Angaiah S, Dhanusuraman R (2022) MXene Based sensing materials: current status and future perspectives. ES Energy Environ 15:4–14. https://doi.org/10.30919/esee8c618
99. Peng B, Zhao FN, Ping JF, Ying YB (2020) Recent advances in nanomaterial-enabled wearable sensors: material synthesis, sensor design, and personal health monitoring. Small 16(44):2002681. https://doi.org/10.1002/smll.202002681
100. Liu J, Liu K, Pan X, Bi K, Zhou F, Lu P, Lei M (2022) A flexible semidry electrode for long-term, high-quality electrocardiogram monitoring. Adv Compos Hybrid Mater 6(1):13. https://doi.org/10.1007/s42114-022-00596-y
101. Li J-W, Huang B-S, Chang C-H, Chiu C-W (2023) Advanced Electrospun AgNPs/rGO/PEDOT:PSS/TPU nanofiber electrodes: stretchable, self-healing, and perspiration-resistant wearable devices for enhanced ECG and EMG monitoring. Adv Compos Hybrid Mater 6(6):231. https://doi.org/10.1007/s42114-023-00812-3
102. Yang MY, Ye ZL, Ren YC, Farhat M, Chen PY (2023) Recent advances in nanomaterials used for wearable electronics. Micromachines 14(3):603. https://doi.org/10.3390/mi14030603
103. Beach C, Krachunov S, Pope J, Fafoutis X, Piechocki RJ, Craddock I, Casson AJ (2018) An Ultra Low Power Personalizable wrist worn ECG Monitor Integrated with IoT infrastructure. IEEE ACCESS 6:44010–44021. https://doi.org/10.1109/ACCESS.2018.2864675
104. Celik N, Manivannan N, Strudwick A, Balachandran W (2016) Graphene-enabled electrodes for electrocardiogram monitoring. Nanomaterials 6(9):156. https://doi.org/10.3390/nano6090156
105. Dey R, Samanta PK, Chokda RP, De BP, Appasani B, Srinivasulu A, Philibert N (2023) Graphene-based electrodes for ECG signal monitoring: fabrication methodologies, challenges and future directions. Cogent Eng 10(1)
106. Prasad AS, Jayaram MN, Swamy K, N., Madhukar BS (2022) Graphene nano-platelets polyvinyl alcohol nanocomposite electrode for real time ECG signal acquisition. Biosens Bioelectronics: X 12:100255. https://doi.org/10.1016/j.biosx.2022.100255
107. Elango PFM, Dhanabalan SS, Robel MR, Elango SP, Walia S, Sriram S, Bhaskaran M (2023) Dry electrode geometry optimization for wearable ECG devices. Appl Phys Rev 10(4):041408
108. Yamamoto Y, Yamamoto D, Takada M, Naito H, Arie T, Akita S, Takei K (2017) Efficient skin temperature sensor and stable gel-less sticky ECG sensor for a wearable flexible healthcare patch. Adv Healthc Mater 6(17):1700495. https://doi.org/10.1002/adhm.201700495
109. Ribeiro HD, Arnold A, Howard JP, Shun-Shin MJ, Zhang Y, Francis DP, Zolgharni M (2022) ECG-based real-time arrhythmia monitoring using quantized deep neural networks: a feasibility study. Comput Biol Med 143:105249. https://doi.org/10.1016/j.compbiomed.2022.105249
110. Zhang C, Zhou Y, Gu SK, Wu ZR, Wu WJ, Liu CM, Tang Y (2016) Prediction of hERG potassium channel blockage by chemical category approaches. Toxicol Res 5(2):570–582. https://doi.org/10.1039/c5tx00294j
111. Al Rahhal MM, Bazi Y, Al Zuair M, Othman E, BenJdira B (2018) Convolutional neural networks for Electrocardiogram classification. J Med Biol Eng 38(6):1014–1025. https://doi.org/10.1007/s40846-018-0389-7
112. Ko WY, Siontis KC, Attia ZI, Carter RE, Kapa S, Ommen SR, Noseworthy PA (2020) Detection of hypertrophic cardiomyopathy using a convolutional neural network-enabled Electrocardiogram. J Am Coll Cardiol 75(7):722–733. https://doi.org/10.1016/j.jacc.2019.12.030
113. Xu J, Yin JY, Fang YS, Xiao X, Zou YJ, Wang SL, Chen J (2023) Deep learning assisted ternary electrification layered triboelectric membrane sensor for self-powered home security. Nano Energy 113:108524. https://doi.org/10.1016/j.nanoen.2023.108524
114. Acharya UR, Fujita H, Oh SL, Hagiwara Y, Tan JH, Adam M (2017) Application of deep convolutional neural network for automated detection of myocardial infarction using ECG signals. Inf Sci 415:190–198. https://doi.org/10.1016/j.ins.2017.06.027
115. Fiorina L, Maupain C, Gardella C, Manenti V, Salerno F, Socie P, Marijon E (2022) Evaluation of an ambulatory ECG analysis platform using deep neural networks in routine clinical practice. J Am Heart Assoc 11(18):e026196. https://doi.org/10.1161/JAHA.122.026196
116. Grogan M, Lopez-Jimenez F, Cohen-Shelly M, Dispenzieri A, Attia ZI, Ezzedine A, Murphree OF (2021) Artificial Intelligence-enhanced Electrocardiogram for the early detection of Cardiac Amyloidosis. Mayo Clin Proc 96(11):2768–2778. https://doi.org/10.1016/j.mayocp.2021.04.023. Jr.
117. Barrett PM, Komatireddy R, Haaser S, Topol S, Sheard J, Encinas J, Topol EJ (2014) Comparison of 24-hour Holter monitoring with 14-day Novel Adhesive Patch Electrocardiographic Monitoring. Am J Med 127(1):95.e11. https://doi.org/10.1016/j.amjmed.2013.10.003
118. Stern S, Tzivoni D (1974) Early detection of silent ischaemic heart disease by 24-hour electrocardiographic monitoring of active subjects. Br Heart J 36(5):481–486
119. Lobodzinski SS (2013) ECG Patch monitors for Assessment of Cardiac Rhythm abnormalities. Prog Cardiovasc Dis 56(2):224–229. https://doi.org/10.1016/j.pcad.2013.08.006

120. Nault I, André P, Plourde B, Leclerc F, Sarrazin JF, Philippon F, Champagne J (2019) Validation of a novel single lead ambulatory ECG monitor - Cardiostat™ - compared to a standard ECG Holter monitoring. J Electrocardiol 53:57–63. https://doi.org/10.1016/j.jelectrocard.2018.12.011
121. Elgendi M, Fletcher R, Liang Y, Howard N, Lovell NH, Abbott D, Ward R (2019) The use of photoplethysmography for assessing hypertension. Npj Digit Med 2(1):60. https://doi.org/10.1038/s41746-019-0136-7
122. Hu GH, Wang SL, Yu JY, Zhang JX, Sun YP, Kong DS (2022) A facile and scalable patterning approach for ultrastretchable liquid metal features. Lab Chip 22(24):4933–4940. https://doi.org/10.1039/d2lc00872f
123. Li JH, Xia BL, Xiao X, Huang ZF, Yin JY, Jiang YW, Chen J (2023) Stretchable thermoelectric fibers with three-dimensional interconnected Porous Network for Low-Grade Body Heat Energy Harvesting. ACS Nano 17(19):19232–19241. https://doi.org/10.1021/acsnano.3c05797
124. Liao JH, Majidi C, Sitti M (2023) Liquid Metal Actuators: a comparative analysis of Surface Tension Controlled Actuation. Adv Mater. https://doi.org/10.1002/adma.202300560
125. Wang ML, Feng SX, Bai C, Ji K, Zhang JX, Wang SL, Kong DS (2023) Ultrastretchable MXene Microsupercapacitors Small 19(21). https://doi.org/10.1002/smll.202300386
126. Madeiro JPV, Cortez PC, Monteiro JM, Brayner A (2018) Developments and applications for ECG Signal Processing. Modeling, Segmentation, and Pattern Recognition. Developments and applications for ECG Signal Processing. Modeling, Segmentation, and Pattern Recognition
127. Liu C, Kim JT, Kwak SS, Hourlier-Fargette A, Avila R, Vogl J, Rogers JA (2021) Wireless, skin-interfaced devices for pediatric critical care: application to continuous, noninvasive blood pressure monitoring. Adv Healthc Mater 10(17):2100383. https://doi.org/10.1002/adhm.202100383
128. Wang YH, Yin L, Bai YZ, Liu SY, Wang L, Zhou Y, Huang YG (2020) Electrically compensated, tattoo-like electrodes for epidermal electrophysiology at scale. Sci Adv 6(43):eabd0996. https://doi.org/10.1126/sciadv.abd0996
129. Meng KY, Xiao X, Wei WX, Chen GR, Nashalian A, Shen S, Chen J (2022) Wearable pressure sensors for pulse wave monitoring. Adv Mater 34(21):2109357. https://doi.org/10.1002/adma.202109357
130. Baek S, Lee Y, Baek J, Kwon J, Kim S, Lee S, Jung S (2022) Spatiotemporal measurement of arterial pulse waves enabled by wearable active-matrix pressure sensor arrays. ACS Nano 16(1):368–377. https://doi.org/10.1021/acsnano.1c06695
131. Kaisti M, Panula T, Leppänen J, Punkkinen R, Tadi MJ, Vasankari T, Pänkäälä M (2019) Clinical assessment of a non-invasive wearable MEMS pressure sensor array for monitoring of arterial pulse waveform, heart rate and detection of atrial fibrillation. Npj Digit Med 2:39. https://doi.org/10.1038/s41746-019-0117-x
132. Fu Y, Zhao S, Wang LQ, Zhu R (2019) A wearable Sensor using structured silver-particle Reinforced PDMS for Radial arterial pulse Wave Monitoring. Adv Healthc Mater 8(17):1900633. https://doi.org/10.1002/adhm.201900633
133. He J, Xiao P, Lu W, Shi JW, Zhang L, Liang Y, Chen T (2019) A Universal high accuracy wearable pulse monitoring system via high sensitivity and large linearity graphene pressure sensor. Nano Energy 59:422–433. https://doi.org/10.1016/j.nanoen.2019.02.036
134. Shin YE, Lee JE, Park Y, Hwang SH, Chae HG, Ko H (2018) Sewing machine stitching of polyvinylidene fluoride fibers: programmable textile patterns for wearable triboelectric sensors. J Mater Chem A 6(45):22879–22888. https://doi.org/10.1039/c8ta08485h
135. Fan WJ, He Q, Meng KY, Tan XL, Zhou ZH, Zhang GQ, Wang ZL (2020) Machine-knitted washable sensor array textile for precise epidermal physiological signal monitoring. Sci Adv 6(11):eaay2840. https://doi.org/10.1126/sciadv.aay2840
136. Fang YS, Zou YJ, Xu J, Chen GR, Zhou YH, Deng WL, Chen J (2021) Ambulatory cardiovascular monitoring via a machine-learning-assisted textile triboelectric sensor. Adv Mater 33(41):2104178. https://doi.org/10.1002/adma.202104178
137. Shyamkumar P, Rai P, Oh S, Ramasamy M, Harbaugh RE, Varadan V (2014) Wearable wireless cardiovascular monitoring using textile-based nanosensor and nanomaterial systems. Electronics (Basel)
138. Zhao X, Chang A, Li J, Xu J, Hollister J, Che ZY, Chen J (2023) Air-Permeable Textile Bioelectronics for Wearable Energy Harvesting and active sensing. Adv Mater Technol 8(8). https://doi.org/10.1002/admt.202201703
139. Gowri A, Kumar NA, Anand BSS (2021) Recent advances in nanomaterials based biosensors for point of care (PoC) diagnosis of Covid-19-A minireview. TrAC Trends Anal Chem 137:116205. https://doi.org/10.1016/j.trac.2021.116205
140. Inan H, Poyraz M, Inci F, Lifson MA, Baday M, Cunningham BT, Demirci U (2017) Photonic crystals: emerging biosensors and their promise for point-of-care applications. Chem Soc Rev 46(2):366–388. https://doi.org/10.1039/c6cs00206d
141. Koh A, Kang D, Xue Y, Lee S, Pielak RM, Kim J, Rogers JA (2016) A soft, wearable microfluidic device for the capture, storage, and colorimetric sensing of sweat. Sci Translational Medicne 8(366):366ra165. https://doi.org/10.1126/scitranslmed.aaf2593
142. Li S, Ma Z, Cao ZL, Pan LJ, Shi Y (2020) Advanced wearable microfluidic sensors for healthcare monitoring. Small 16(9):1903822. https://doi.org/10.1002/smll.201903822
143. Satta S, Rockwood SJ, Wang KD, Wang SL, Mozneb M, Arzt M, Sharma A (2023) Microfluidic organ-chips and stem cell models in the fight against COVID-19. Circul Res 132(10):1405–1424. https://doi.org/10.1161/CIRCRESAHA.122.321877
144. Gao W, Emaminejad S, Nyein HYY, Challa S, Chen KV, Peck A, Javey A (2016) Fully integrated wearable sensor arrays for multiplexed perspiration analysis. Nature 529(7587):509. https://doi.org/10.1038/nature16521
145. Siontis KC, Noseworthy PA, Attia ZI, Friedman PA (2021) Artificial intelligence-enhanced electrocardiography in cardiovascular disease management. Nat Reviews Cardiol 18(7):465–478. https://doi.org/10.1038/s41569-020-00503-2
146. Khor SM, Choi J, Won P, Ko SH (2022) Challenges and strategies in developing an enzymatic wearable sweat glucose Biosensor as a practical Point-Of-Care Monitoring Tool for type II diabetes. Nanomaterials 12(2):221. https://doi.org/10.3390/nano12020221
147. Saldanha DJ, Cai AQ, Courchesne NMD (2023) The evolving role of proteins in wearable sweat biosensors. ACS Biomater Sci Engueering 9(5):2020–2047. https://doi.org/10.1021/acsbiomaterials.1c00699
148. Wang KD, Huang K, Jiang GQ (2018) Enhanced removal of aqueous acetaminophen by a laccase-catalyzed oxidative coupling reaction under a dual-pH optimization strategy. Sci Total Environ 616:1270–1278. https://doi.org/10.1016/j.scitotenv.2017.10.191
149. Lee H, Song C, Hong YS, Kim MS, Cho HR, Kang T, Kim DH (2017) Wearable/disposable sweat-based glucose monitoring device with multistage transdermal drug delivery module. Sci Adv 3(3):e1601314. https://doi.org/10.1126/sciadv.1601314
150. Tu JB, Min JH, Song Y, Xu CH, Li JH, Moore J, Gao W (2023) A wireless patch for the monitoring of C-reactive protein in sweat. Nat Biomedical Eng 7(10):1293–1306. https://doi.org/10.1038/s41551-023-01059-5

151. Bandodkar AJ, Jia WZ, Yardimci C, Wang X, Ramirez J, Wang J (2015) Tattoo-based noninvasive glucose monitoring: a proof-of-Concept Study. Anal Chemistrytical 87(1):394–398. https://doi.org/10.1021/ac504300n
152. Lipani L, Dupont BGR, Doungmene F, Marken F, Tyrrell RM, Guy RH, Ilie A (2018) Non-invasive, transdermal, path-selective and specific glucose monitoring via a graphene-based platform. Nat Nanotechnol 13(6):504. https://doi.org/10.1038/s41565-018-0112-4
153. Adler A, Holder D (2021) Electrical impedance tomography: methods, history and applications. https://doi.org/10.1201/9780429399886
154. Chen JS, Arianpour B, Wang KD, Wang SL, Yin JY, Zhang YR, Hsiai TK (2023) Emerging nanomaterials to enhance electrochemical impedance spectroscopy for biomedical applications. Front Mater 10:1146045. https://doi.org/10.3389/fmats.2023.1146045
155. Martinsen OG (2004) Some basic techniques in bioimpedance research. Medical Physics
156. Stupin DD, Kuzina EA, Abelit AA, Emelyanov AK, Nikolaev DM, Ryazantsev MN, Dubina MV (2021) Bioimpedance Spectroscopy: basics and applications. ACS Biomater Sci Eng 7(6):1962–1986. https://doi.org/10.1021/acsbiomaterials.0c01570
157. Wang SL, Nie YY, Zhu HY, Xu YR, Cao ST, Zhang JX, Kong DS (2022) Intrinsically stretchable electronics with ultrahigh deformability to monitor dynamically moving organs. Sci Adv 8(13):eabl5511. https://doi.org/10.1126/sciadv.abl5511
158. Putensen C, Hentze B, Muenster S, Muders T (2019) Electrical impedance tomography for cardio-pulmonary monitoring. J Clin Med 8(8):1176. https://doi.org/10.3390/jcm8081176
159. Zhang K, Guo R, Li MK, Yang F, Xu SH, Abubakar A (2021) Supervised descent learning for thoracic electrical impedance tomography. IEEE Trans Inf Technol Biomed 68(4):1360–1369. https://doi.org/10.1109/TBME.2020.3027827
160. Darma PN, Baidillah MR, Sifuna MW, Takei M (2020) Real-time dynamic imaging method for flexible Boundary Sensor in Wearable Electrical Impedance Tomography. IEEE Sens J 20(16):9469–9479. https://doi.org/10.1109/JSEN.2020.2987534
161. Huang JJ, Hung YH, Wang JJ, Lin BS (2016) Design of wearable and wireless electrical impedance tomography system. Measurement 78:9–17. https://doi.org/10.1016/j.measurement.2015.09.031
162. Yao JF, Chen HJ, Xu ZF, Huang JS, Li JP, Jia JB, Wu HT (2020) Development of a Wearable Electrical Impedance Tomographic Sensor for gesture Recognition with Machine Learning. Ieee J Biomedical Health Inf 24(6):1550–1556. https://doi.org/10.1109/JBHI.2019.2945593
163. Khan TA, Ling S (2019) Review on Electrical Impedance Tomography: Artificial Intelligence methods and its applications. Algorithms 12:88. https://doi.org/10.3390/a12050088
164. Adler A, Boyle A (2017) Electrical impedance tomography: tissue properties to Image measures. IEEE Trans Inf Technol Biomed 64(11):2494–2504. https://doi.org/10.1109/TBME.2017.2728323
165. Kireev D, Sel K, Ibrahim B, Kumar N, Akbari A, Jafari R, Akinwande D (2022) Continuous cuffless monitoring of arterial blood pressure via graphene bioimpedance tattoos. Nat Nanotechnol 17(8):864. https://doi.org/10.1038/s41565-022-01145-w
166. Solà J, Adler A, Santos A, Tusman G, Sipmann FS, Bohm SH (2011) Non-invasive monitoring of central blood pressure by electrical impedance tomography: first experimental evidence. Med Biol Eng Comput 49(4):409–415. https://doi.org/10.1007/s11517-011-0753-z
167. Hu HJ, Huang H, Li MH, Gao XX, Yin L, Qi RX, Xu S (2023) A wearable cardiac ultrasound imager. Nature 613(7945). https://doi.org/10.1038/s41586-022-05498-z
168. La TG, Le LH (2022) Flexible and wearable Ultrasound device for medical applications: a review on materials, structural designs, and current challenges. Adv Mater Technol 7(3):2100798. https://doi.org/10.1002/admt.202100798
169. Ma ZW, Bourquard C, Gao QM, Jiang SB, De Iure-Grimmel T, Huo R, Li JY (2022) Controlled tough bioadhesion mediated by ultrasound. Science 377(6607):751–755. https://doi.org/10.1126/science.abn8699
170. Wang CH, Chen XY, Wang L, Makihata M, Liu HC, Zhou T, Zhao XH (2022) Bioadhesive ultrasound for long-term continuous imaging of diverse organs. Science 377(6605):517-eab02542. https://doi.org/10.1126/science.abo2542
171. Jiang S, Zhang T, Zhou Y, Lai P, Huang Y (2023) Wearable ultrasound bioelectronics for healthcare monitoring. Innovation 4(4):100447–100447. https://doi.org/10.1016/j.xinn.2023.100447
172. Dong K, Peng X, Wang ZL (2020) Fiber/Fabric-Based Piezoelectric and Triboelectric Nanogenerators for Flexible/Stretchable and Wearable Electronics and Artificial Intelligence. Adv Mater 32(5):1902549. https://doi.org/10.1002/adma.201902549
173. Lee HR, Kim CC, Sun JY (2018) Stretchable Ionics - A Promising candidate for Upcoming Wearable devices. Adv Mater 30(42):1704403. https://doi.org/10.1002/adma.201704403
174. Gupta P, Moghimi MJ, Jeong Y, Gupta D, Inan OT, Ayazi F (2020) Precision wearable accelerometer contact microphones for longitudinal monitoring of mechano-acoustic cardiopulmonary signals. npj Digit Med 3(1):19. https://doi.org/10.1038/s41746-020-0225-7
175. Cotur Y, Kasimatis M, Kaisti M, Olenik S, Georgiou C, Güder F (2020) Stretchable Composite Acoustic Transducer for Wearable Monitoring of Vital signs. Am Heart J 30(16):1910288. https://doi.org/10.1002/adfm.201910288
176. Nayeem MOG, Lee S, Jin H, Matsuhisa N, Jinno H, Miyamoto A, Someya T (2020) All-nanofiber-based, ultrasensitive, gas-permeable mechanoacoustic sensors for continuous long-term heart monitoring. Proc Natl Acad Sci 117(13):7063–7070. https://doi.org/10.1073/pnas.1920911117
177. Wang Y, Yokota T, Someya T (2021) Electrospun nanofiber-based soft electronics. NPG Asia Mater 13(1):22. https://doi.org/10.1038/s41427-020-00267-8
178. Krittanawong C, Rogers AJ, Johnson KW, Wang Z, Turakhia MP, Halperin JL, Narayan SM (2021) Integration of novel monitoring devices with machine learning technology for scalable cardiovascular management. Nat Reviews Cardiol 18(2):75–91. https://doi.org/10.1038/s41569-020-00445-9
179. Haskell WL (2003) Cardiovascular disease prevention and lifestyle interventions: effectiveness and efficacy. J Cardiovasc Nurs 18(4):245–255. https://doi.org/10.1097/00005082-200309000-00003
180. Ketola E, Sipila R, Makela M (2000) Effectiveness of individual lifestyle interventions in reducing cardiovascular disease and risk factors. J Article Meta-Analysis Res Support Annals Med 32(4):239–251. https://doi.org/10.3109/07853890009011767
181. Masana L, Ros E, Sudano I, Angoulvant D, Ibarretxe Gerediaga D, Murga Eizagaechevarria N, Piedecausa M (2017) Is there a role for lifestyle changes in cardiovascular prevention? What, when and how? Atherosclerosis Supplements 26:2–15. https://doi.org/10.1016/S1567-5688(17)30020-X
182. Bayoumy K, Gaber M, Elshafeey A, Mhaimeed O, Dineen EH, Marvel FA, Elshazly MB (2021) Smart wearable devices in cardiovascular care: where we are and how to move forward. Nat Reviews Cardiol 18(8):581–599. https://doi.org/10.1038/s41569-021-00522-7
183. Lobelo F, Kelli HM, Tejedor SC, Pratt M, McConnell MV, Martin SS, Welk GJ (2016) The wild wild west: a Framework to integrate mHealth Software Applications and Wearables to Support

Physical Activity Assessment, Counseling and interventions for Cardiovascular Disease Risk reduction. Prog Cardiovasc Dis 58(6):584–594. https://doi.org/10.1016/j.pcad.2016.02.007

184. Pevnick JM, Birkeland K, Zimmer R, Elad Y, Kedan I (2018) Wearable technology for cardiology: an update and framework for the future. Trends Cardiovasc Med 28(2):144–150. https://doi.org/10.1016/j.tcm.2017.08.003
185. Kario K (2020) Management of hypertension in the Digital Era Small Wearable Monitoring devices for remote blood pressure monitoring. Hypertension 76(3):640–650. https://doi.org/10.1161/HYPERTENSIONAHA.120.14742
186. Konstantinidis D, Iliakis P, Tatakis F, Thomopoulos K, Dimitriadis K, Tousoulis D, Tsioufis K (2022) Wearable blood pressure measurement devices and new approaches in hypertension management: the digital era. J Hum Hypertrnsion 36(11):945–951. https://doi.org/10.1038/s41371-022-00675-z
187. Baka T, Simko F (2021) Monitoring non-dipping heart rate by Consumer-Grade wrist-worn devices: an Avenue for Cardiovascular Risk Assessment in Hypertension. Front Cardiovasc Med 8:711417. https://doi.org/10.3389/fcvm.2021.711417
188. Cabral S (2021) Wearable remote monitoring in heart failure care – where do we stand? Rev Port Cardiol 40. https://doi.org/10.1016/j.repc.2021.02.009
189. DeVore AD, Wosik J, Hernandez AF (2019) The future of Wearables in Heart failure patients. JACC: Heart Fail 7(11):922–932. https://doi.org/10.1016/j.jchf.2019.08.008
190. Inan OT, Pouyan MB, Javaid AQ, Dowling S, Etemadi M, Dorier A, Klein L (2018) Novel Wearable Seismocardiography and Machine Learning algorithms can assess clinical status of heart failure patients. Circ: Heart Fail 11(1):e004313. https://doi.org/10.1161/CIRCHEARTFAILURE.117.004313
191. Tao QX, Liu SW, Zhang JY, Jiang J, Jin ZL, Huang YQ, Chen HX (2023) Clinical applications of smart wearable sensors. Iscience 26(9):107485. https://doi.org/10.1016/j.isci.2023.107485
192. Xiao X, Yin JY, Shen SP, Che ZY, Wan X, Wang SL, Chen J (2022) Advances in solid-state fiber batteries for wearable bioelectronics. Curr Opin Solid State Mater Sci 26(6):101042. https://doi.org/10.1016/j.cossms.2022.101042
193. Dunn J, Runge R, Snyder M (2018) Wearables and the medical revolution. Per Med 15(5):429–448. https://doi.org/10.2217/pme-2018-0044
194. Hughes A, Shandhi MMH, Master H, Dunn J, Brittain E (2023) Wearable devices in Cardiovascular Medicine. Circul Res 132(5):652–670. https://doi.org/10.1161/CIRCRESAHA.122.322389
195. Lee SP, Ha G, Wright DE, Ma YJ, Sen-Gupta E, Haubrich NR, Ghaffari R (2018) Highly flexible, wearable, and disposable cardiac biosensors for remote and ambulatory monitoring. npj Digit Med 1:2. https://doi.org/10.1038/s41746-017-0009-x
196. Chen S, Qi J, Fan S, Qiao Z, Yeo JC, Lim CT (2021) Flexible wearable sensors for Cardiovascular Health monitoring [Journal Article Research Support, Non-U.S. Gov't. Adv Healthc Mater 10(17):e2100116–e2100116. https://doi.org/10.1002/adhm.202100116
197. Gehr S, Russmann C (2022) Shaping the future of cardiovascular medicine in the new era of wearable devices. Nat Reviews Cardiol 19(8):501–502. https://doi.org/10.1038/s41569-022-00729-2
198. Torres-Soto J, Ashley EA (2020) Multi-task deep learning for cardiac rhythm detection in wearable devices. Npj Digit Med 3(1):116–116. https://doi.org/10.1038/s41746-020-00320-4