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Blood flow status
Heart rate
Pulse waveform
Respiratory
HIGH
Arteriosclerosis
Blood pressure
Heart failure
Arrhythmia

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Heartbeat electro-language: Exploring piezoelectric technologies for cardiovascular health monitoring

Yun Ke[1,#], Tong Li[2,#], Jun Li[3,#], Mingliang Pei[1], Xinming Wang[4], Weichang Xie[4], Shuting Zhuang[1], Xiaofeng Ye[4,*], Zhou Li[5,*], Zuankai Wang[6,*], Fan Yang[1,*]

[1] *Department of Orthopaedics, Shanghai Key Laboratory for Prevention and Treatment of Bone and Joint Diseases, Shanghai Institute of Traumatology and Orthopaedics, Ruijin Hospital, Shanghai Jiao Tong University School of Medicine, Shanghai 200025, China.*

[2]*Department of Mechanical Engineering, City University of Hong Kong, Hong Kong 999077, China.*

[3]*Department of Materials Science and Engineering, University of Wisconsin–Madison, Madison, WI 53706, USA.*

[4]*Department of Cardiovascular Surgery, Ruijin Hospital, Shanghai Jiao Tong University School of Medicine, Shanghai 200025, China*

[5]*Beijing Institute of Nanoenergy and Nanosystems, Chinese Academy of Sciences, Beijing 101400, China*

[6]*Department of Mechanical Engineering, The Hong Kong Polytechnic University, Hong Kong 999077, China*

[#]These authors contributed equally to this work.

*Indicates corresponding authors:

E-mail: Fan Yang (yf12498@sjtu.edu.cn); Zuankai Wang (zk.wang@polyu.edu.hk); Zhou Li (zli@binn.cas.cn); Xiaofeng Ye (xiaofengye@hotmail.com)

Abstract

Cardiovascular diseases remain the leading cause of global morbidity and mortality, underscoring the urgent need for advanced technologies capable of continuous, noninvasive, and intelligent monitoring. Piezoelectric sensors, owing to their inherent electromechanical transduction, high sensitivity, and self-powered operation, offer a compelling pathway for next-generation cardiovascular health monitoring. In this review, we summarize recent advances in piezoelectric materials, from zero- to three-dimensional architectures, and their integration into wearable and implantable platforms. Key applications include the assessment of arterial health via pulse wave velocity and vascular stiffness, cuffless blood pressure estimation, and the monitoring of cardiopulmonary functions such as heart rate, respiratory rhythm, and cardiac acoustics. We also highlight emerging strategies such as passive wireless communication enabled by surface acoustic wave principles, and the development of multimodal systems that concurrently capture mechanical, optical, and chemical signals. The convergence of piezoelectric technologies with artificial intelligence and Internet of Things frameworks enables real-time signal processing, remote access, and personalized medical interventions. Finally, we discuss current challenges in material biocompatibility, encapsulation, signal fidelity, and clinical translation, and outline future directions for advancing high-performance piezoelectric systems for intelligent cardiovascular diagnostics and connected healthcare.

Keywords

Cardiovascular monitoring; Piezoelectric effect; Flexible pressure sensor; Self-powered devices; AI-enabled monitoring

1. Introduction

Cardiovascular diseases (CVDs), encompassing conditions such as coronary artery disease, arrhythmias, hypertension, and stroke, pose one of the most critical public health challenges globally [1-3]. According to the World Heart Federation's *World Heart Report 2023*, CVDs were responsible for approximately 20.5 million deaths in 2021, accounting for 31% of all global mortality and ranking as the leading cause of death. These statistics underscore the urgent need for early diagnosis, continuous monitoring, and precision interventions [4].

Driven by aging populations and changes in lifestyle, the incidence and burden of CVDs have been steadily rising, with increasingly complex epidemiological patterns [5, 6]. The progression and outcome of CVDs are influenced by a range of factors, including genetic predisposition, environmental exposure, socioeconomic status, and behavioral habits. Addressing this multifactorial challenge requires a holistic approach that integrates personalized risk profiling, environmental context, and targeted medical strategies [7, 8].

Real-time, high-fidelity monitoring plays a vital role in improving cardiovascular outcomes by facilitating early detection, reducing the likelihood of acute events, and enhancing survival and quality of life [9, 10]. Functional assessment of cardiovascular health involves tracking cardiac and vascular mechanical activity such as heartbeat, contraction, and expansion, alongside hemodynamic indicators (blood pressure, shear stress, blood flow velocity), biochemical markers (oxygen saturation, glucose, lactate), and electrical signals such as electrocardiograms [11]. To support such multidimensional sensing, a variety of technologies have been developed, including mechanical [12], optical [13], electrochemical [14], and electrophysiological methods [15] (**Fig. 1**).

Conventional systems such as electrocardiography (ECG) and Holter monitors provide high diagnostic accuracy for electrical abnormalities but are constrained by rigid electrodes and external power supplies, limiting their long-term wearability and adaptability to dynamic environments [16-18]. Photoplethysmography (PPG) often suffers from motion artifacts and environmental interference, while force-based sensors, such as piezoresistive and capacitive types, may exhibit baseline drift, low sensitivity, and high energy consumption.

In contrast, piezoelectric sensors offer several advantages, including high sensitivity to micro-mechanical deformations, fast response, mechanical flexibility, and self-powered operation, making them particularly suitable for long-term, continuous cardiovascular monitoring across multiple parameters [19, 20]. These devices also enable remote data transmission and support personalized interventions for timely clinical decision-making [21] (**Table 1**). As a result, the development of compact, high-performance piezoelectric monitoring systems has emerged as a central focus of cardiovascular sensing research [22].

Overall, piezoelectric technology offers a robust and scalable platform for capturing subtle cardiovascular mechanical signals with high precision and energy efficiency. Its seamless integration with flexible materials and emerging electronics, combined with advances in nanotechnology, positions it as a promising solution for real-time monitoring, early diagnosis, and personalized cardiovascular care in future healthcare systems.

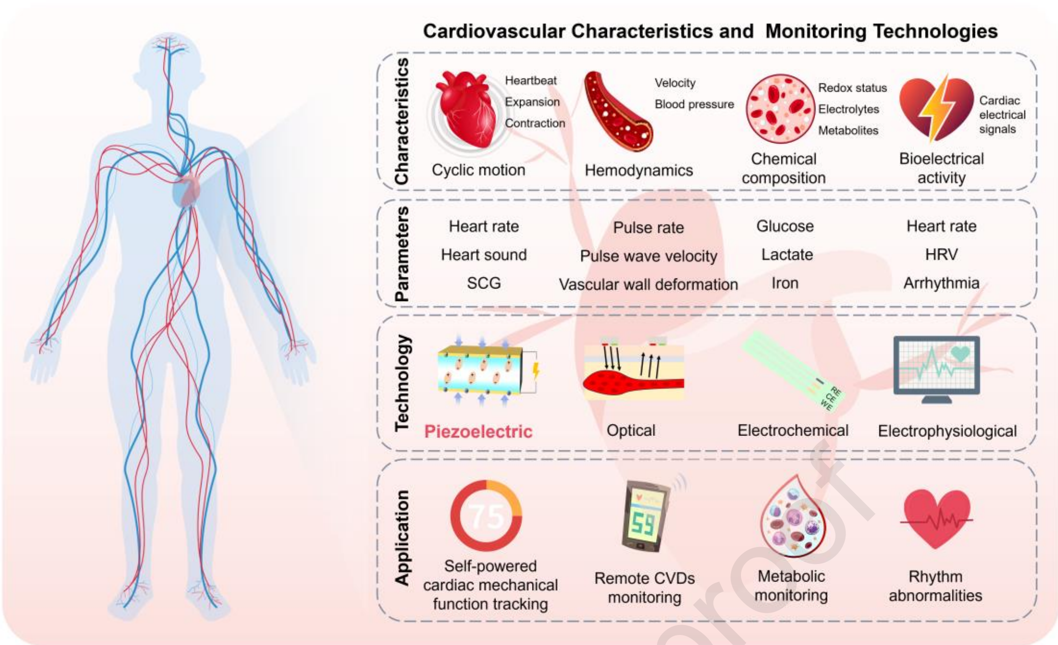

Fig. 1. Cardiovascular characteristics, monitoring parameters, and enabling technologies for health management. Overview of key cardiovascular features, including cyclic motion, hemodynamics, chemical composition, and bioelectrical activity. Corresponding physiological parameters such as heart rate, pulse wave velocity, and vascular deformation are monitored using piezoelectric, optical, electrochemical, and electrophysiological technologies. These approaches support applications in self-powered functional tracking, remote cardiovascular disease monitoring, metabolic analysis, and rhythm disorder detection.

2 Fundamentals of piezoelectric cardiovascular sensing

2.1 Mechanistic principles and material systems

The piezoelectric effect refers to the generation of electric charges on the surface of non-centrosymmetric materials when subjected to mechanical stress, resulting from polarization changes within their crystal lattice (**Fig. 2a**) [23-25]. This bidirectional transduction, which is mechanical-to-electrical (direct effect) and electrical-to-mechanical (inverse effect), forms the basis for both sensing [26, 27] and energy harvesting applications [28, 29]. In cardiovascular health monitoring, piezoelectric materials enable real-time, energy-efficient, and highly sensitive detection of mechanical signals generated by cardiac and vascular activity. These include pulse wave propagation, arterial wall deformation, and cardiac contractile motion, which are closely linked to hemodynamic parameters such as blood pressure (BP), vascular stiffness, and myocardial function.

Piezoelectric materials can be classified into four structural categories: zero-dimensional (0D), one-dimensional (1D), two-dimensional (2D), and three-dimensional (3D), each offering distinct advantages in sensitivity, flexibility, biocompatibility, and device integration (**Fig. 2b**) [30, 31]. 0D materials such as ZnO and $BaTiO_3$ nanoparticles exhibit high surface-to-volume ratios and interfacial tunability, which enhance charge transfer and compatibility with flexible matrices [32, 33]. Other 0D candidates, such as quantum dots and halide perovskites, enable multimodal signal coupling through enhanced local fields and optoelectronic interactions [34]. 1D materials, including PVDF nanofibers and gallium nitride (GaN) nanowires, offer superior mechanical compliance and directional electromechanical response [35-38]. PVDF fibers show strong responses to subtle pulse deformations, while GaN nanowires offer stable outputs for implantable biosensing [39, 40]. 2D materials such as monolayer MoS_2 and hexagonal boron nitride (h-BN) exhibit in-plane piezoelectricity due to the absence of inversion symmetry at the atomic scale [41-43]. Their ultrathin geometry, flexibility, and electronic functionality support integration into conformal, wearable, and vascular-interfacing devices. Additional 2D candidates, such as MXenes, also offer promising performance due to their high conductivity and tunable surface chemistry [44]. 3D materials, including PZT (lead zirconate titanate) ceramics and porous PVDF/$BaTiO_3$ composites, exhibit strong piezoelectric coupling and mechanical robustness, making them well-suited for energy harvesting, and ultrasound-driven applications [45-47]. Architected foams and negative Poisson's ratio structures further enhance deformation sensitivity [48, 49], while metal–organic frameworks (MOFs) expand possibilities for lightweight, tunable, and potentially degradable piezoelectric platforms.

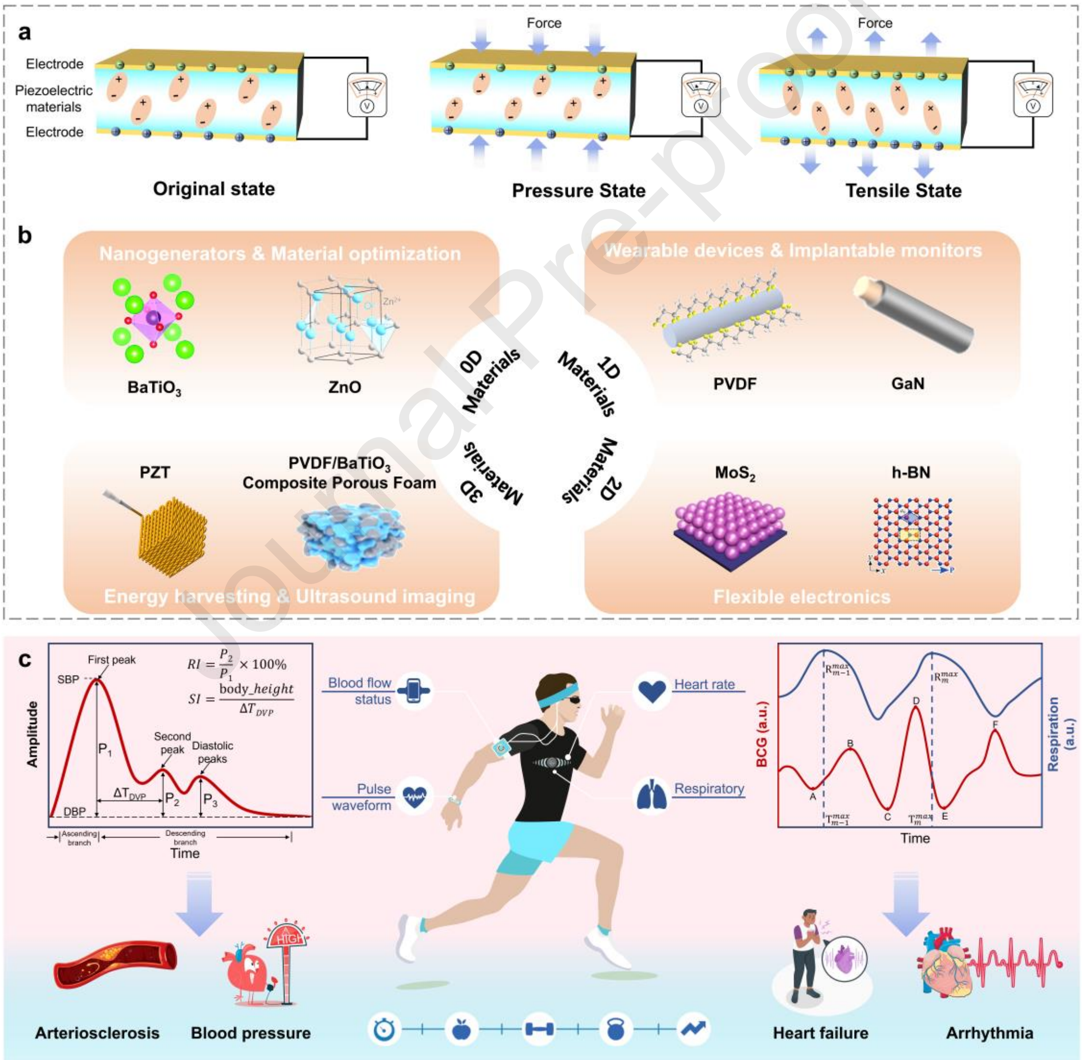

Fig. 2. Fundamentals, materials, and applications of piezoelectric technology for cardiovascular monitoring. (a) Schematic of the piezoelectric effect under compressive and tensile stress. (b) Representative piezoelectric materials spanning 0D to 3D configurations for applications in energy harvesting, flexible electronics, and bio-integrated devices. Reproduced with permission [32]. Copyright 2012, Royal Society

of Chemistry. Reproduced with permission [33]. Copyright 2016, WILEY-VCH. Reproduced with permission [37]. Copyright 2024, Elsevier. Reproduced with permission [38]. Copyright 2019, Elsevier. Reproduced with permission [41]. Copyright 2019, Elsevier. Reproduced with permission [42]. Copyright 2012, American Chemical Society. Reproduced with permission [45]. Copyright 2020, Elsevier. Reproduced with permission [46]. Copyright 2021, American Chemical Society. (c) Schematic of a multimodal wearable and implantable piezoelectric system for real-time cardiovascular and cardiopulmonary monitoring. Pulse waveform features such as stiffness index (SI) and reflection index (RI), along with ballistocardiogram (BCG) and respiration signals, enable assessment of BP, arteriosclerosis, heart failure, and arrhythmia.

These dimensional categories exhibit complementary advantages and limitations, as summarized in **Table 2**. 0D materials excel in nanoscale integration but often suffer from mechanical fragility. 1D systems are suitable for conformal wearables but may face long-term stability challenges. 2D materials offer ultrathin, multifunctional sensing interfaces, although issues of biocompatibility and manufacturing scalability remain [50-52]. 3D architectures provide strong mechanical coupling and are well-suited for implantable devices, energy harvesting, and ultrasound stimulation, especially when developed with biocompatible or biodegradable matrices. Coordinated innovation across all material dimensions will be essential for enabling long-term, personalized cardiovascular monitoring.

As illustrated in **Fig. 2c**, piezoelectric systems integrated into wearable and implantable platforms can capture multimodal signals, including arterial pulse waveforms, BCG, and respiration patterns. These mechanical signals correlate with physiological parameters such as systolic and diastolic blood pressure, SI, RI, cardiac output, and respiratory rhythm. Such sensing capability supports early diagnosis and dynamic tracking of hypertension, arteriosclerosis, heart failure, and arrhythmias.

Combined with wireless transmission and artificial intelligence (AI)-enabled data processing, piezoelectric technologies offer a powerful foundation for next-generation cardiovascular health management.

2.2 Technological advances and evolution

Piezoelectric technology, which converts mechanical energy into electrical signals, has emerged as a compelling solution for cardiovascular health monitoring (**Fig. 3**). In 1953, Eddleman et al. [53] first applied piezoelectric transducers to record chest wall-induced pulse waves, laying the groundwork for later developments. In 1985, Karr et al. [54] utilized PVDF-based transducers for cardiovascular parameter screening via mechanical coupling. In 1991, Arbeille et al. [55] combined piezoelectric sensors with Doppler systems to measure hemodynamic parameters, with clinical validation in pregnancy and fetal hypoxia.

Advances in AI, wearable electronics, and Internet of Things (IoT) technologies have since expanded the capabilities of piezoelectric systems for real-time, high-precision monitoring [56-58]. In 2003, McLaughlin et al. [59] developed a dual-sensor system to measure pulse wave velocity (PWV) and assess vascular stiffness. In 2006, Sato et al. [60] introduced a PZT-based system for monitoring heart and respiratory rates in anesthetized mice, employing custom analog and digital circuits to reduce signal noise.

Significant progress was made in 2014 when Rogers et al. [61] designed an ultra-thin, flexible PZT energy harvester for cardiac signal acquisition, capable of powering pacemakers. They later integrated PZT with silicon nanomembranes to develop a noninvasive arterial pulse wave sensor [62]. In recent years, Park et al. [63] introduced a self-powered piezoelectric pulse sensor for real-time arterial pulse monitoring, while Wang et al. [64] incorporated ultra-thin piezoelectric ultrasonic transducers to enable skin-adherent devices for deep vascular BP monitoring. Further innovations include a highly flexible electronic tattoo platform by Ha et al. [65] in 2019, and a 2022 chip-less wireless electronic skin system based on GaN, developed by Kim [66], that enables passive signal acquisition without rigid integrated circuits. Together, these milestones mark the evolution of piezoelectric systems from basic mechanical sensors to intelligent, miniaturized platforms that are central to the future of cardiovascular diagnostics and digital health.

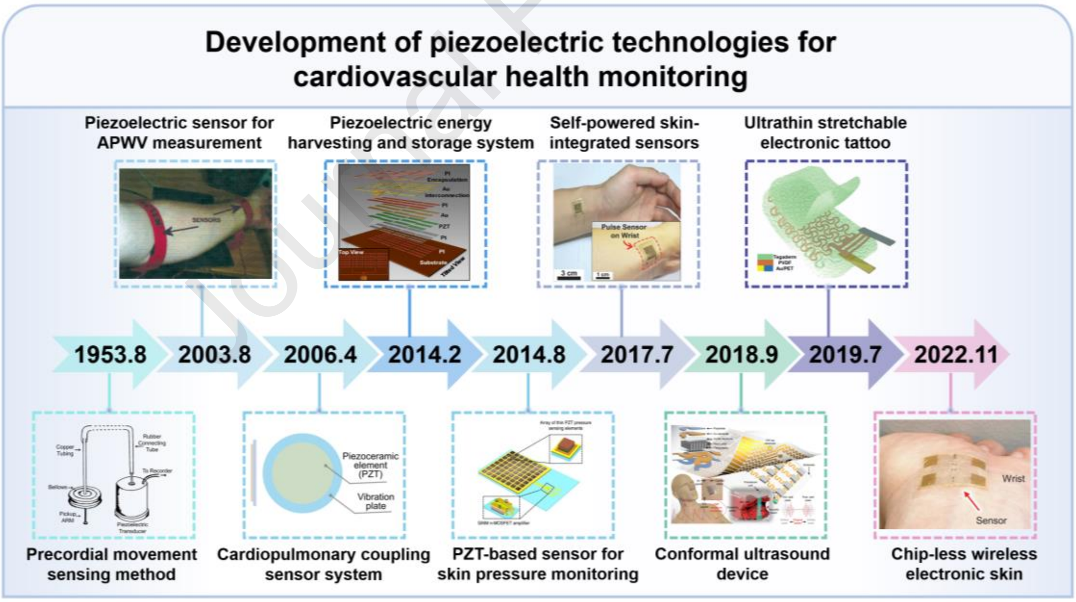

Fig. 3. Milestones in the development of piezoelectric technologies for cardiovascular health monitoring. Chronological overview of key innovations in piezoelectric-based cardiovascular monitoring devices from 1953 to 2022. The timeline includes early mechanical sensing of precordial movements, cardiopulmonary coupling systems, energy-harvesting and self-powered skin sensors, PZT-based pressure monitors, conformal ultrasonic devices, and the latest chip-less wireless electronic skin platforms. Reproduced with permission [53]. Copyright 1953, Wolters Kluwer Health. Reproduced with permission [59]. Copyright 2003, IOP Publishing. Reproduced with permission [60]. Copyright 2006, Springer Nature. Reproduced with permission [61].

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3 Applications in cardiovascular monitoring

3.1 Hemodynamic-based arterial health assessment

3.1.1 Implantable sensors

Over the past two decades, implantable electronic systems have shown considerable advantages for continuous hemodynamic monitoring and in vivo therapeutic applications [67]. Cheng et al. [68] developed a self-powered and visualized monitoring system based on a 200 μm polarized PVDF piezoelectric thin film. The device, wrapped around the ascending aorta of a pig, harvested biomechanical energy and provided real-time feedback on blood flow status with high linearity ($R^2 > 0.99$) and sensitivity (173 mV/mmHg), significantly outperforming previous devices (**Fig. 4a**). Expanding on structural integration, Pan et al. [69] reported a piezoelectric vascular stent featuring a sawtooth geometry, fabricated via FDM-based 3D printing with embedded electric fields. Composed of sodium potassium niobate and PVDF-HFP, the device demonstrated stable voltage output under simulated pressure fluctuations and offered reliable pressure sensitivity for intravascular sensing (**Fig. 4b**).

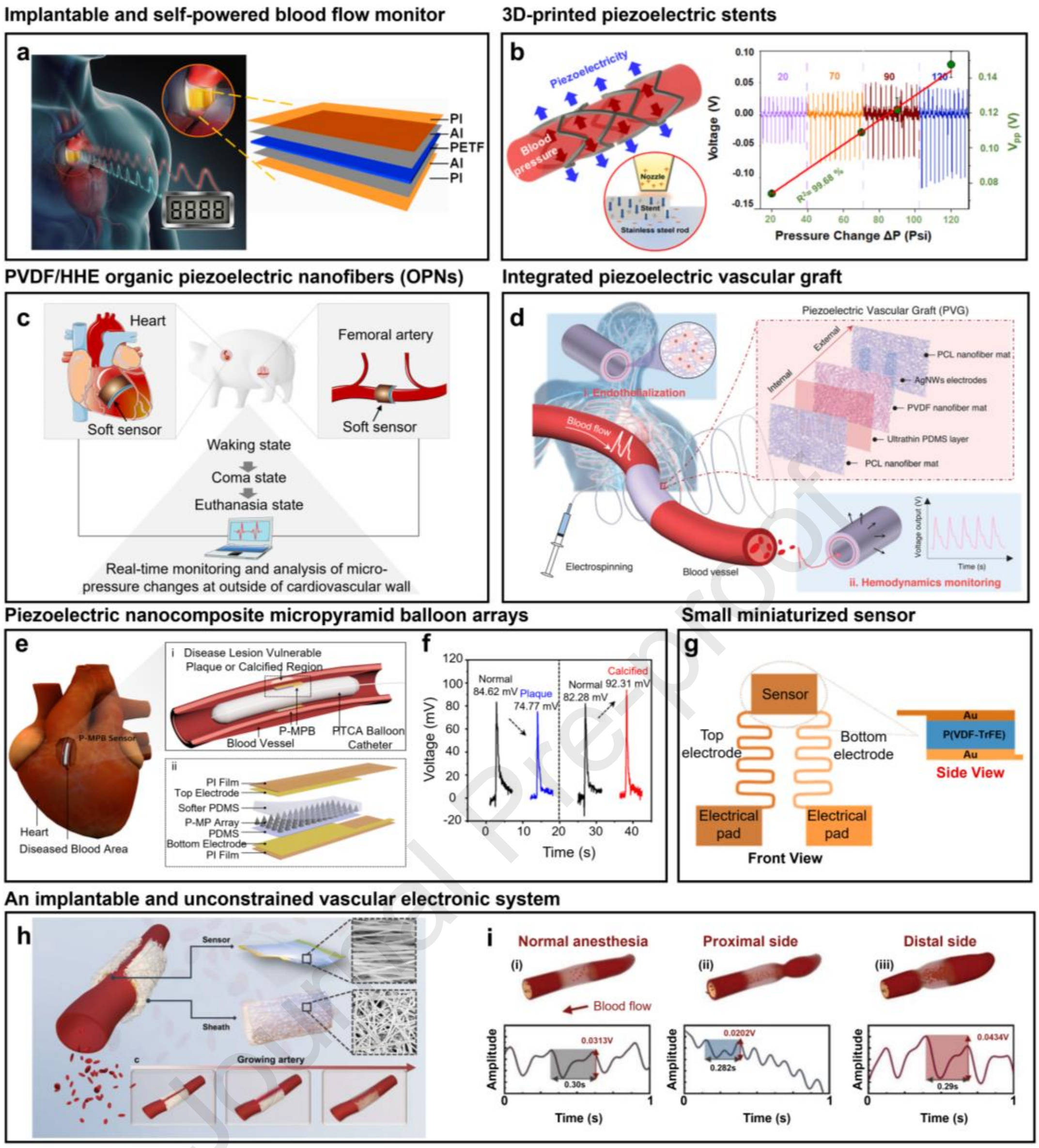

Fig. 4. Implantable piezoelectric sensors for arterial health monitoring. (a) Multilayer implantable sensor for self-powered blood flow monitoring. Reproduced with permission [68]. Copyright 2016, Elsevier. (b) 3D-printed piezoelectric stent for real-time pressure sensing and hemodynamic analysis. Reproduced with permission [69]. Copyright 2024, American Chemical Society. (c) Soft PVDF/HHE piezoelectric nanofiber sensor for monitoring cardiovascular micro-pressure changes across physiological states. Reproduced with permission [70]. Copyright 2019, American Chemical Society. (d) Integrated piezoelectric vascular graft (PVG) featuring electrospun nanofibers for enhanced endothelium compatibility and continuous hemodynamic monitoring. Reproduced with permission [71]. Copyright 2024, WILEY-VCH. (e) Piezoelectric micro-pyramid balloon sensor for detecting pressure changes in diseased vessels. (f) Output voltage signals from different lesion types under balloon compression Reproduced with permission [72]. Copyright 2023, American Chemical Society. (g) Schematic of a miniaturized piezoelectric force sensor with vertical and planar electrode configurations. Reproduced with permission [73]. Copyright 2020,

American Chemical Society. (h) Conceptual illustration of an unconstrained vascular electronic system with sheath-assisted implantation. (i) Representative pulse waveforms from a stenosed artery model under different anesthesia and positional conditions. Reproduced with permission [74]. Copyright 2024, WILEY-VCH.

In pursuit of enhanced performance and biocompatibility, Li et al. [70] designed core–shell PVDF/HHE nanofibers with aligned β-phase nanocrystals. The resulting soft piezoelectric sensor was capable of capturing micro-pressure variations on cardiovascular walls with high sensitivity. Implanted into a pig model, it accurately reflected variations in vascular elasticity and pathological states such as conduction blocks and thrombus formation (**Fig. 4c**). Further integrating sensing and tissue regeneration functions, Ma et al. [71] developed a piezoelectric vascular graft using electrospun PVDF/PCL nanofibers. This graft supported real-time hemodynamic monitoring while maintaining favorable mechanical properties and endothelialization, offering a promising platform for long-term vascular health tracking (**Fig. 4d**). Chang et al. [75] demonstrated a self-powered implantable pressure sensor by embedding ZnO nanofillers into PVDF nanofibers, achieving stable performance when adhered to cardiovascular tissues such as the heart and femoral artery, and enabling real-time tracking of vascular condition changes.

In the context of localized vascular assessment, Kang et al. [72] introduced a piezoelectric micro-pyramid balloon catheter (p-MPB) sensor. Featuring microstructured piezoelectric arrays on a balloon surface, this device enabled direct measurement of vascular stiffness in coronary arteries. Ex vivo experiments on pig hearts confirmed its ability to distinguish mechanical variations in diseased tissues, supporting its potential for the early diagnosis of vascular pathologies such as

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atherosclerosis and aneurysms (**Figs. 4e, f**). To support catheter-based intraoperative feedback, Gil et al. [73] designed a force sensor incorporating a P(VDF-TrFE) layer for integration at the tip of medical catheters. The sensor enabled real-time monitoring of vascular contact pressure, which is critical for preventing endothelial damage and fluid leakage during surgical procedures (**Fig. 4g**). Toward adaptive long-term monitoring, Tang et al. [74] proposed an unconstrained vascular electronic system composed of fixed piezoelectric sensors embedded in a growable sheath. Implanted around developing arteries in rabbits, the system wirelessly recorded hemodynamic signals and captured pathological changes such as stenosis and retrograde blood flow, indicated by attenuated or distorted pulse waveforms (**Figs. 4h, i**). Several biologically compatible and degradable materials have been found to exhibit excellent piezoelectric responses [76, 77]. Cheng et al. [78] fabricated a fully organic force sensor using amino acid crystal films and polyaniline electrodes encapsulated in PLA. The device exhibited excellent stability and a broad detection range, offering suitability for long-term in vivo monitoring of physiological pressures.

Collectively, these advances demonstrate the growing versatility of implantable piezoelectric systems for enabling the real-time, high-sensitivity assessment of arterial function and hemodynamic status, laying a foundational framework for in vivo diagnosis and intervention in cardiovascular diseases.

3.1.2 Wearable sensors

Wearable piezoelectric sensors provide a noninvasive, low-power, and continuous means of capturing subtle arterial wall deformations, enabling real-time assessment of vascular mechanical properties. By analyzing pulse wave signals collected from superficial arteries, such devices can extract surrogate indicators of arterial stiffness, offering early insights into vascular aging and arteriosclerosis [79-81]. Due to the significantly higher arterial hardness of patients with arteriosclerosis, features extracted based on pulse signals can be easily used to diagnose the disease, such as the time delay between P_1 and P_2 (Δt_{DVP}), the time delay between P_1 and P_3 (PPT), the PWV, the stiffness index (SI), and the radial augmentation index (AIr) (**Fig. 2c**). The calculation methods for the indicators used in this work are as follows [82]:

$$\Delta t_{DVP} = t_{p_2} - t_{p_1} \quad (1)$$

$$PPT = t_{p_3} - t_{p_1} \quad (2)$$

$$PWV = 0.8 \times \frac{2\Delta L}{\Delta t_{DVP}} \quad (3)$$

$$SI = \frac{H}{PPT} \quad (4)$$

$$AI_r = \frac{h_2}{h_1} \quad (5)$$

In equations (1, 2), t_{p1}, t_{p2}, and t_{p3} are the times corresponding to P_1, P_2, and P_3, respectively. In equations (3, 4), ΔL is the length from jugulum to symphysis, 0.8 is a recommended correction factor for international standardization, and H is the height of the tester [83]. In equation (5), h_1 and h_2 are the heights of P_1 and P_2, respectively.

Park et al. [84] developed an e-skin based on microstructured PVDF composites, which allowed the continuous tracking of pulse dynamics with sensitivity to environmental changes, such as skin temperature fluctuations (**Fig. 5b**). Complementarily, Han et al. [85] proposed a high-density piezoelectric sensor array integrated into a flexible platform, enabling simultaneous detection and spatial mapping

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of arterial and venous pulses (**Fig. 5a**). The system demonstrated strong signal fidelity and temporal resolution, supporting the derivation of pulse features relevant to arterial stiffness monitoring under practical wearable conditions. Li et al. [86] also developed a flexible piezoelectric sensor comprising randomly stacked PVDF/DA nanofiber (NF) thin films (**Fig. 5c**). The device conformed to various body surfaces (e.g., chest, neck, and wrist), accurately capturing weak mechanical stimuli caused by blood pulsation. Under different physiological states, the device demonstrated robust capabilities in detecting diaphragm contractions and peripheral arterial wall changes with precision and speed. To address the mechanical mismatch between conventional sensors and the human epidermis, Kim et al. [66] innovatively reported a chip-free wireless electronic skin based on surface acoustic wave (SAW) sensors, fabricated from ultra-thin, freestanding single-crystal piezoelectric GaN films (**Fig. 5d**). This SAW-based electronic skin enables highly sensitive, low-power, and long-term sensing of strain, ultraviolet (UV) exposure, and ionic concentrations in sweat. Researchers demonstrated pulse monitoring for up to one week (**Fig. 5e**), providing a cost-effective and versatile platform for wireless health monitoring devices with low power consumption and high sensitivity. Tian et al. [87] introduced an ultrathin, conformal piezoelectric device based on a 3 μm P(VDF-TrFE) film, fabricated via spin-coating and aqueous exfoliation techniques. The device exhibited excellent skin conformity and sensitivity, enabling stable pulse waveform acquisition under dynamic conditions and across multiple arterial sites (**Fig. 5f**). This work underscores the potential of skin-integrated piezoelectric platforms for high-resolution, distributed vascular health monitoring in wearable applications. These advances collectively underscore the growing potential of wearable piezoelectric systems for enabling high-resolution, noninvasive monitoring of arterial health.

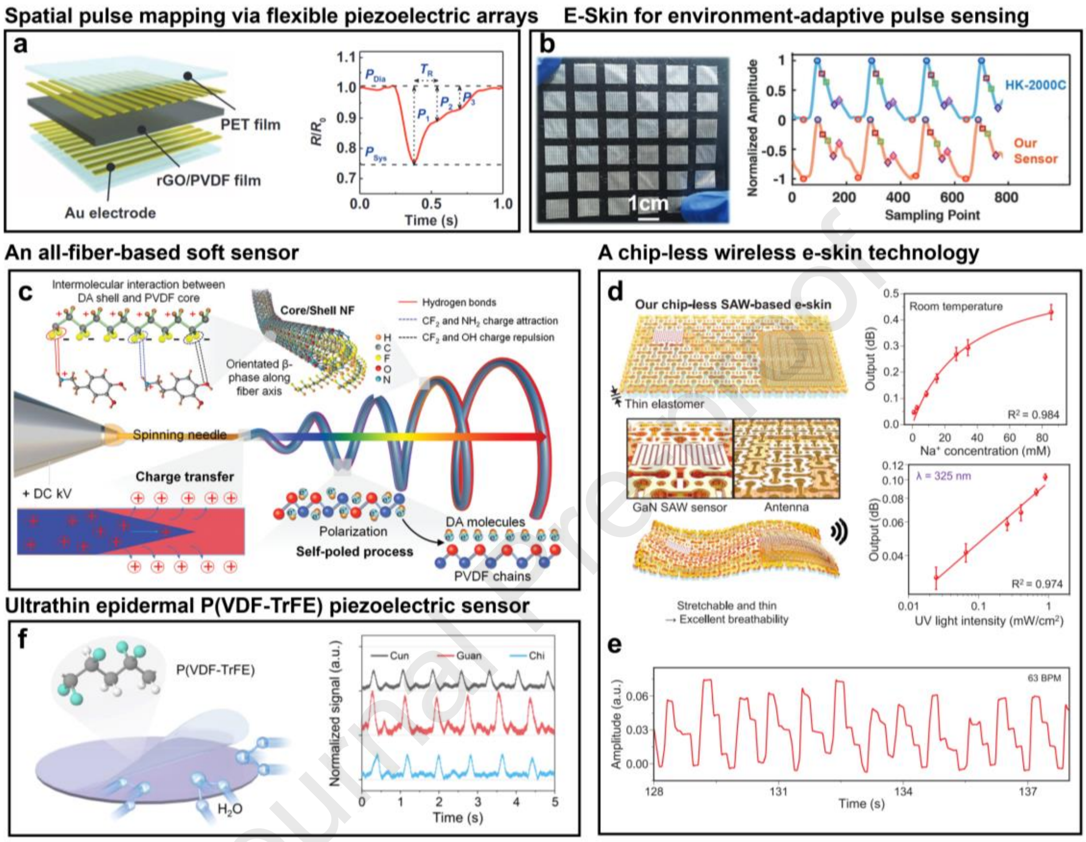

Fig. 5. Wearable piezoelectric sensors for arterial health monitoring. (a) Spatial pulse mapping using a flexible rGO/PVDF composite sensor array sandwiched between gold electrodes. Reproduced with permission [84]. Copyright 2015, American Association for the Advancement of Science. (b) Batch fabrication and performance evaluation of flexible environment-adaptive pulse sensors. Reproduced with permission [85]. Copyright 2022, WILEY-VCH. (c) All-fiber PVDF/DA core–shell piezoelectric nanofibers fabricated via electrospinning, showing oriented β-phase formation induced by intermolecular interactions. Reproduced with permission [86]. Copyright 2021, WILEY-VCH. (d) Chip-less wireless e-skin platform based on GaN SAW sensors, responsive to Na^+ concentration and ultraviolet light intensity. (e) Wireless arterial pulse monitoring using the GaN SAW-based e-skin. Reproduced with permission [66]. Copyright 2022, American Association for the Advancement of Science. (f) Schematic and signal output of an ultrathin P(VDF–TrFE) epidermal sensor fabricated via aqueous exfoliation. Reproduced with permission [87]. Copyright 2023, American Chemical Society.

In recent years, micromechanical ultrasonic transducers have found increasing applications in medical fields, including volumetric ultrasound imaging [88] and intravascular imaging [89], and they are now emerging as key components in wearable systems for arterial stiffness monitoring. Jiang et al. [90] proposed a 1.5 × 1.5 mm^2 array of 5 MHz piezoelectric micromachined ultrasonic transducers (PMUT) designed for tracking radial artery wall motion. The complete ultrasonic measurement system offers advantages such as compact size and low power consumption, demonstrating significant potential for continuous cardiovascular health monitoring. Ding et al. [91] developed a compact, low-power pulsed-wave Doppler flowmeter based on AlN PMUTs, integrating custom electronics and a blood flow simulation system to achieve real-time monitoring of flow velocity and direction. The device accurately captured Doppler frequency and spectral changes linked to pulsatile flow, demonstrating feasibility for vascular function assessment and future wearable applications. Gami et al. [92] introduced a PMUT-based pulse wave imaging system for evaluating central arterial mechanics in wearable and at-home settings. Compared to a clinical-grade probe, the PMUT array achieved high accuracy in pulse wave velocity estimation (error <5%) and remained robust under noisy conditions, confirming its suitability for low-power, high-precision arterial stiffness monitoring. These studies highlight the strong potential of PMUT technology as a foundation for next-generation wearable systems for continuous vascular health assessment.

3.2 Cuffless BP monitoring

Pulse wave characteristics are critical indicators for evaluating vascular health and cardiovascular function. Key parameters, such as wave peaks and wave velocity, are closely associated with BP, arterial stiffness, and vascular elasticity. In recent years, piezoelectric technology has emerged as a core tool in pulse wave monitoring due to its high sensitivity and rapid response capabilities.

Yi et al. [93] proposed a mathematical model for arterial pulse piezoelectric dynamics (**Fig. 6a**), investigating the relationship between arterial BP waves and piezoelectric arterial pulse waves across nano- to macro-scale functional layer thicknesses. Their findings demonstrated the feasibility of using single and multiple piezoelectric arterial pulse sensors to monitor BP (**Figs. 6b**, **c**). By advancing the understanding of arterial pulse piezoelectric responses, these results contribute to the development of portable, wearable, and continuous cardiovascular health monitoring technologies.

3.2.1 Single-site piezoelectric measurement

Continuous monitoring of BP remains a considerable challenge due to the low quality of the signal and the lack of an accurate transfer function to convert the sensor signal to a BP value. Min et al. [94] developed an ultra-thin piezoelectric sensor combining a PDMS passivation layer and a medical-grade adhesive layer, achieving high sensitivity (0.062 kPa^{-1}), rapid response time (23 ms), and excellent mechanical stability (**Fig. 6d**). Through mechanical loading tests exceeding 50,000 cycles, the sensor demonstrated exceptional stability and consistency in both dynamic and static environments. Wang et al. [95] developed a tissue-adhesive piezoelectric soft sensor (TPSS) that integrates a mussel-inspired adhesive hydrogel layer with a flexible PVDF-based piezoelectric architecture to enable real-time, continuous BP monitoring during cardiac surgery. The sensor exhibits excellent mechanical compliance, strong bioadhesion, and an ultrathin, lightweight form factor, allowing stable attachment to dynamic tissue surfaces such as the beating heart. In vivo experiments demonstrated high signal fidelity and strong agreement with catheter-based measurements (**Fig. 6e**).

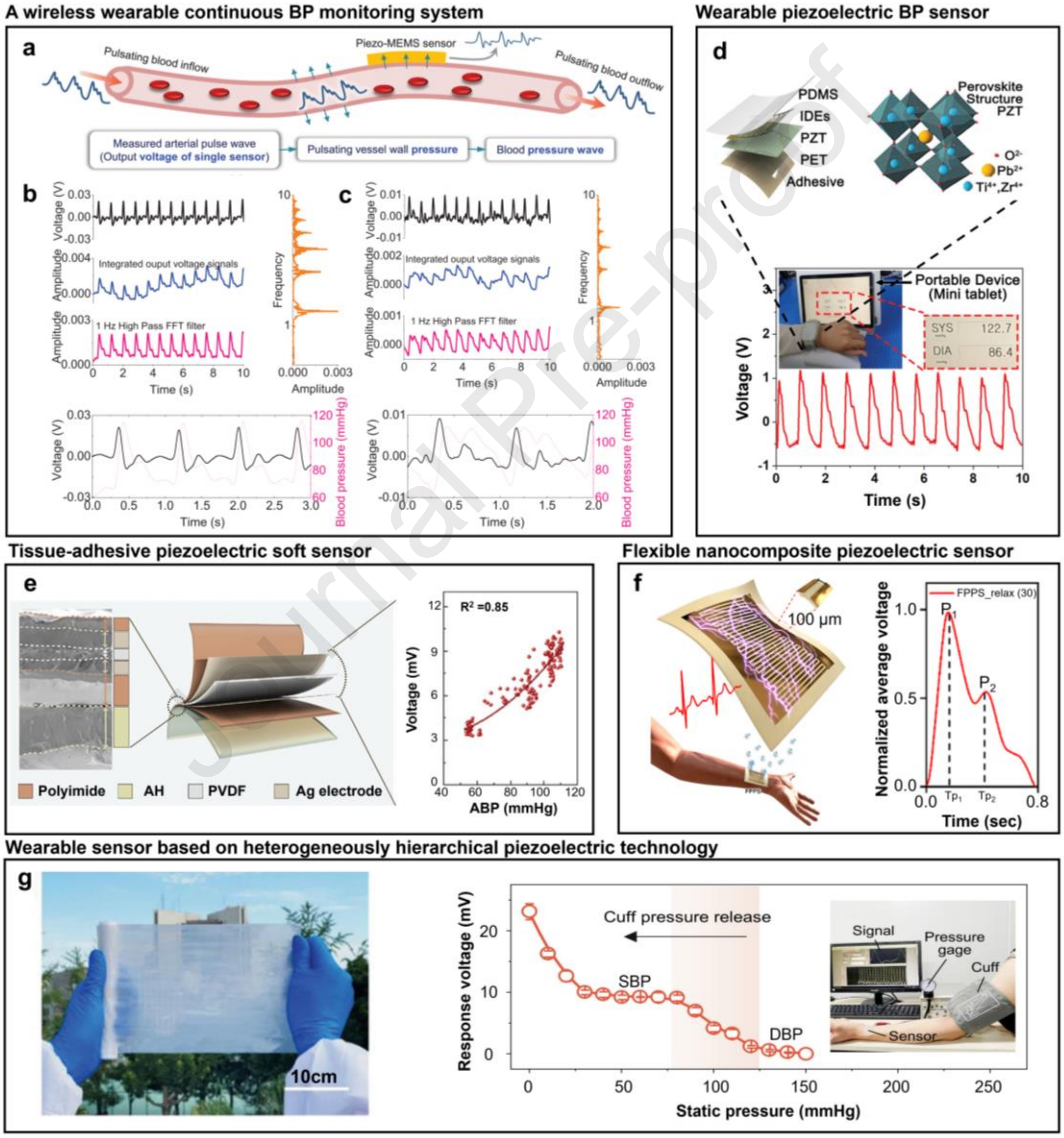

Fig. 6. Piezoelectric sensors for cuffless BP monitoring based on single-site pulse waveform analysis. (a) Schematic of arterial pressure transmission and sensing using a wearable piezoelectric sensor. (b, c) Pulse waveform acquisition from the finger and elbow using a cutaneous piezoelectric device, with corresponding signal processing and BP correlation. Reproduced with permission [93]. Copyright 2022, WILEY-VCH. (d) Structure and output of a flexible piezoelectric BP sensor integrated with a portable

device for wireless pulse signal transmission. Reproduced with permission [94]. Copyright 2023, WILEY-VCH. (e) SEM image and exploded view of a TPSS, revealing its tightly bonded multilayer structure, which enables a clear correlation between arterial BP and output voltage. Reproduced with permission [95]. Copyright 2023, WILEY-VCH. (f) Schematic of a flexible nanocomposite piezoelectric sensor with improved dispersion and permeability for high-fidelity pulse detection. Reproduced with permission [96]. Copyright 2023, American Chemical Society. (g) Large-area hierarchical piezoelectric composite film for cuffless monitoring of systolic/diastolic pressure and real-time cardiovascular signals. Reproduced with permission [97]. Copyright 2024, WILEY-VCH.

Conductive fillers are favored for their unique interfacial polarization and accompanying percolation effects, which bring new ways to achieve higher piezoelectricity [98]. Inspired by the structure of muscle fibers, Su et al. [99] developed a piezoelectric textile based on PDA-coated BTO (barium titanate) nanoparticles. The incorporation of functional fillers enhanced interfacial polarization and percolation effects, leading to a significant improvement in piezoelectric performance. The resulting textile demonstrated high sensitivity in detecting pulse wave features, enabling its use in BP and cardiovascular condition assessment. Similarly, Kim et al. [96] embedded surface-functionalized PZT nanoparticles into a PVDF matrix (**Fig. 6f**), which enhanced the interfacial polarization and percolation effects, thereby improving the piezoelectric output. The fabricated flexible sensor exhibited high sensitivity for pulse wave monitoring and is applicable for BP and vascular health evaluation. Tian et al. [97] reported a wearable sensor based on heterogeneous layered piezoelectric composites, fabricated using a scalable, non-equilibrium process combining electrospinning and hot pressing. This process layered MXene and boron nitride (BN) nanosheets within a poly(vinylidene fluoride-trifluoroethylene) [P(VDF-TrFE)] matrix, referred to as PT in this study (**Fig. 6g**). The sensor continuously monitored cardiovascular parameters and extracted pulse waveform data from detected signals, which strongly correlated with clinical results. Long-term tracking experiments validated its reliability, showcasing its potential for personalized healthcare applications.

3.2.2 Dual-site sensing and PWV estimation

Pulse transit time (PTT) and PWV are two interdependent metrics that characterize the temporal and spatial dynamics of arterial pulse propagation. PTT, defined as the time for a pulse wave to travel between two arterial sites [100], is influenced by vascular elasticity [101, 102] and has been widely used in arterial stiffness evaluation [103], myocardial ischemia detection [104], and sleep monitoring [105]. PWV, calculated as the ratio of travel distance to PTT, serves as a widely accepted index for arterial stiffness and is strongly associated with cardiovascular risk [106-109]. These parameters, derived from dual-site pulse sensing, provide complementary insights into vascular compliance and circulatory health.

As early as 2006, Fool et al. [110] employed piezoelectric technology to detect radial artery pulsations at the wrist, estimating PTT through experiments involving 17 healthy adults. This study demonstrated the exceptional performance of piezoelectric sensors in capturing arterial pulse wave details, particularly for dynamic monitoring of BP and arterial stiffness. With advances in technology, research has shifted toward more precise and convenient monitoring devices. The development of data analytics has also driven significant progress in pulse arrival time (PAT) research through ML techniques. Liang et al. [111], analyzing data from the MIMIC database, found that PAT sensitivity

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might decrease in individuals with a higher baseline BP, posing challenges to its broad applicability. Shao et al. [112] utilized deep learning (DL) models to extract complex features from large-scale PAT datasets for BP prediction and cardiovascular risk assessment. Compared to traditional linear models, DL methods demonstrate greater capability in managing multivariable interferences and uncovering latent patterns within complex data. Although PAT is closely related to dynamic BP changes, its efficacy as a BP-related parameter is influenced by various factors. Finnegan et al. [113] noted a negative correlation between PAT and BP, but high-load states such as exercise or emotional fluctuations may introduce additional confounding factors, including changes in cardiac preload, afterload, and peripheral resistance.

Continuous, cuffless, and non-invasive BP monitoring through the measurement of PWV is widely regarded as a promising technique for real-time cardiovascular assessment [114]. The Moens–Korteweg (MK) equation [115] and the Hughes equation [116] are commonly employed to establish a relationship between PWV and BP (P).

$$MK\ Equation: PWV = \sqrt{\frac{Eh_0}{2\rho R_0}} \quad \text{......(6)}$$

$$Hughes\ Equation: E = E_0 exp(\alpha P) \quad \text{......(7)}$$

In equations (6, 7), E, h_0, and R_0 represent the elastic (tangential) modulus under BP (P), arterial wall thickness, and arterial radius, respectively; ρ denotes blood density; E_0 is the elastic modulus at zero BP; and α is a material coefficient of the artery. The MK equation assumes a thin arterial wall and fixed radius, which may not hold true for human arteries. Conversely, the Hughes equation is entirely empirical.

To address these limitations, Ma et al. introduced an improved formula for the relationship between PWV and BP by incorporating the Fung hyperelastic model. This formulation was further generalized to encompass both linear elastic and hyperelastic materials, where α and β are determined by the material properties and geometric characteristics of the arteries [117].

$$P = \alpha \cdot PWV^2 + \beta \quad (8)$$

The PWV also can be derived from measurements of the pressure wave on two sites of the arterial tree [118]. In equation (9), the time difference Δt between the arrival of the pulse at each sensor position, together with the distance L between the two sensors, allows the calculation of PWV:

$$PWV = \frac{L}{\Delta t} \quad (9)$$

Clinically, the gold standard for continuous BP monitoring involves the use of fiber-based pressure sensors implanted at the arterial center [119, 120]. However, such methods are highly invasive, increasing patient discomfort and infection risks, rendering them unsuitable for routine monitoring. Li et al. [121] proposed a thin, soft, miniaturized system (TSMS) comprising sensing, active pressure adaptation, and data processing modules (**Fig. 7a**). Two piezoelectric sensors were used to calculate the local PWV and combined with multiple pulse waveform features to establish a BP prediction model. Through the XGBoost algorithm, the PWV and waveform features were mapped to the BP, realizing high-precision and continuous noninvasive BP monitoring. Chen et al. [122] developed a flexible piezoelectric pulse sensor (F-PPS) based on single-crystal III-N thin films, capable of accurately measuring pulse waveforms and calculating physiological parameters such as PTT across multiple arterial sites. The sensor offers high sensitivity, noninvasiveness, and flexibility, enabling real-time detection of pulse waveform changes and making it suitable for continuous cardiovascular health monitoring. In addition to improving the sensitive materials and device structure used to improve the output of piezoelectric sensors, adding an elastomer between the skin and the piezoelectric layer can also improve the signal quality [123, 124]. Zhang et al. [125] investigated the effects of elastic media with varying thicknesses and elastic moduli on PVDF sensor performance. They identified an optimal piezoelectric pulse sensor (PPS) based on PVDF film, integrated dual probes in the sensor, and verified a stable mapping between PWV and BP by measuring local PWV at two locations at a 10 mm pitch, yielding predictions that were highly consistent with those of a conventional electronic sphygmomanometer (**Fig. 7b**). Additionally, Okano et al. [126] described a multimodal cardiovascular monitoring system that combines piezoelectric sensors with other biosignal acquisition technologies. The system improves PWV extraction accuracy through a cross-correlation algorithm and relies only on a dual-sensor arrangement with 1–2 cm spacing, avoiding the dependence of traditional methods on widely spaced measurement points (**Fig. 7c**). Nordine et al. [127] employed a noninvasive system based on piezoelectric/piezo capacitive sensors (PES/PCS) to capture dynamic changes in pulse transit time in a heterogeneous cohort of patients undergoing major surgeries. This system innovatively uses a dual-sensor structure on the wrist to simultaneously measure the pulse wave at two locations, and it accurately extracts the PTT through a cross-correlation algorithm, which in turn calculates the local PWV.

Arrhythmia induces hemodynamic changes in the arteries, which compromise the accuracy of commercial electronic BP monitors [128]. Guo et al. [129] introduced a PVDF-based piezoelectric sensor (**Fig. 7d**) capable of detecting ectopic beats from the radial artery. Kaplan–Meier analysis also confirmed a positive correlation between central PWV-related indices and recurrence risk, demonstrating a stable mapping between PWV and BP status obtained by the dual-sensor approach, which can be used to predict arrhythmic outcomes (**Fig. 7e**). Compared to traditional methods, this approach demonstrates higher sensitivity and accuracy in identifying arrhythmias, enabling real-time capture and analysis of PWV variations and offering new possibilities for clinical applications. Obeid et al. [130] proposed a non-invasive method for measuring central and peripheral PWV by combining piezoelectric sensors with second derivative algorithms. Additionally, Guo et al. [131] developed a multimodal device for cuffless BP measurement using a PVDF piezoelectric sensor array and near-infrared spectroscopy (NIRS). This device calibrates a hemodynamics-based PTT and BP model using arterial parameters, accounting for previously overlooked factors in related studies and thereby reducing BP estimation errors. Katsuura et al. [132] introduced pulse wave monitoring technology based on flexible piezoelectric thin-film arrays, highlighting its advantages in real-time measurement peak characteristics. Their study showed that the multi-point monitoring capability of flexible arrays significantly enhances spatial resolution, facilitating regional vascular condition assessments.

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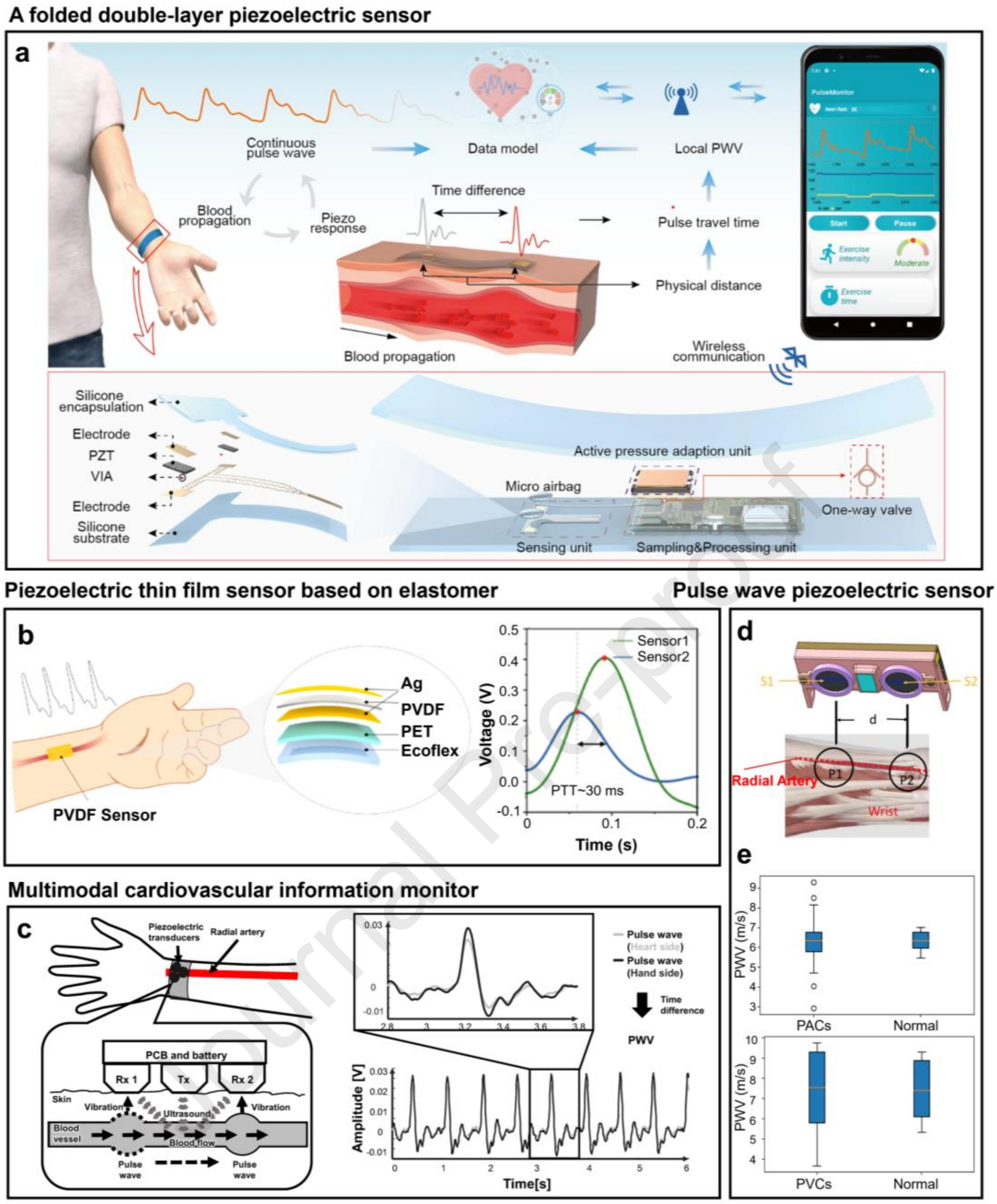

Fig. 7. Piezoelectric sensors for BP and vascular assessment via dual-site PWV measurement. (a) Wireless wristband system integrating folded piezoelectric sensors for continuous BP monitoring and local PWV estimation. Reproduced with permission [121]. Copyright 2023, Springer Nature. (b) Structural diagram and working principle of a PVDF-based sensor fabricated on an elastomeric substrate. Reproduced with permission [125]. Copyright 2024, American Chemical Society. (c) Multimodal monitoring platform integrating piezoelectric, ultrasound, and vibrational sensing for bilateral pulse wave acquisition and PWV extraction. Reproduced with permission [126]. Copyright 2018, Springer Nature. (d) Pulse wave velocity measurement using dual piezoelectric sensors placed along the radial artery. (e) PWV values in patients with premature atrial and ventricular contractions (PACs and PVCs), compared to healthy individuals. Reproduced with permission [129]. Copyright 2021, MDPI.

3.3 Cardiopulmonary monitoring via multiparametric piezoelectric sensing

Recent advances in flexible piezoelectric sensors have supported multiparameter monitoring of heart rate variability (HRV) and the RR interval, combining simultaneous signal acquisition with data fusion to improve diagnostic value [133-135]. These studies emphasize the technical advantages of flexible piezoelectric sensors, including high sensitivity, real-time performance, and environmental friendliness. As early as 2007, Bu et al. [136] proposed a non-contact cardiopulmonary signal monitoring system for sleep, based on a flexible AlN piezoelectric thin-film sensor. This sensor can detect subtle pressure variations on the human back, induced by respiration and heartbeat; when these are combined with empirical mode decomposition (EMD) algorithms, the sensor effectively extracts and separates respiratory and cardiac signals. In the post-COVID-19 era, a high-sensitivity piezoelectric sensor based on PZT has been developed for the simultaneous monitoring and fusion of heart sounds and pulmonary signals, enabling noninvasive cardiopulmonary function assessment in both healthy individuals and discharged pneumonia patients [137]. Wang et al. [138] developed a wearable piezoelectric patch that enables real-time, noninvasive monitoring of cardiopulmonary coupling by synchronously capturing respiration and heartbeat signals.

To solve problems such as poor flexibility and signal stability, Chiu et al. [139] developed a piezoelectric patch sensor based on a curved PVDF structure, achieving a 151% increase in respiratory signal detection efficiency due to the curved design (**Fig. 8a**). This sensor captures heartbeat and respiratory signals with high precision by detecting periodic chest wall deformations and pulsatile vibrations, providing real-time synchronous monitoring. This innovation supports early detection of cardiopulmonary health anomalies. Flexible piezoelectric devices based on 1D inorganic nanomaterials have demonstrated excellent performance. It has been shown that high-quality ZnO nanostructures can be grown on graphene films without catalysts [140]. Park et al. [141] fabricated highly sensitive, flexible pressure sensors by growing ZnO nanotube arrays with controlled positions and dimensions on graphene substrates (**Fig. 8b**). These sensors exhibit high sensitivity (–4.4 kPa^{-1}), enabling accurate monitoring of respiratory and pulse signals and demonstrating utility in the early diagnosis of pulmonary and cardiovascular diseases. The performance of ZnO nanotubes is attributed to their high aspect ratio and ultra-thin wall structure. In recent studies, Maity et al. [142] proposed a fully 3D-printed pyroelectric–piezoelectric nanogenerator (Py-PNG) based on cellulose nanocrystals (CNC) (**Fig. 8c**). This system simultaneously harvests mechanical and thermal energy, functioning as an electronic skin sensor for the early detection of cardiopulmonary dysfunctions. Such integrated sensors open new possibilities for portable monitoring devices and personalized healthcare applications (**Fig. 8d**). Continuous monitoring of arterial pulse via epidermal pressure sensors is crucial for the early detection of cardiovascular disease and personal health assessment. Comparatively, Han et al. [143] utilized a foldable dual-layer piezoelectric sensor to expand monitoring capabilities, capturing not only heartbeats and respiratory sounds but also Korotkoff sounds (**Fig. 8e**). These innovations indicate that flexible multifunctional sensors are becoming a critical development area for cardiovascular health monitoring technologies.

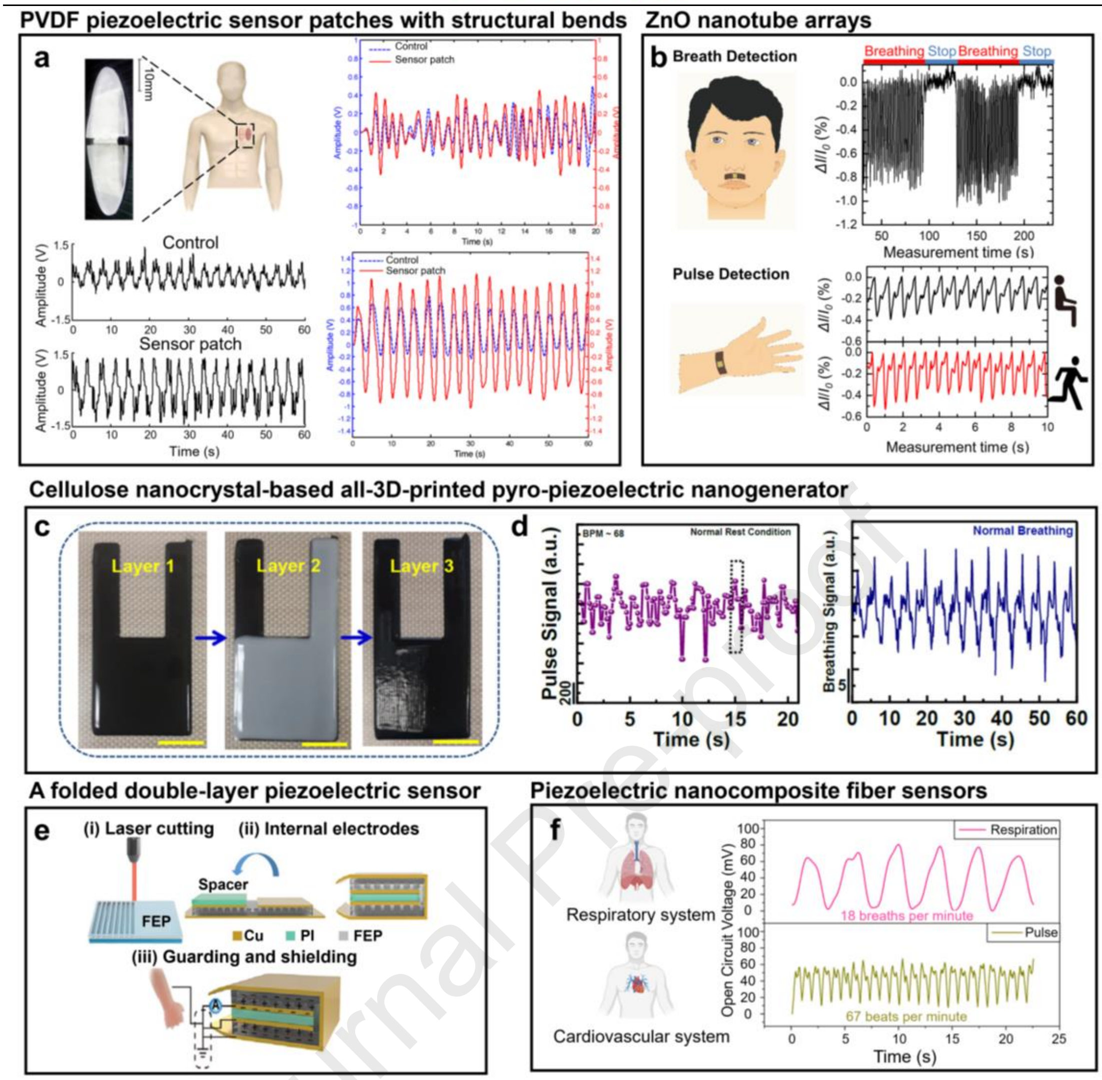

Fig. 8. Piezoelectric sensors for cardiopulmonary signal monitoring. (a) PVDF sensor patches with structural bending for simultaneous respiration and pulse detection on the chest wall. Reproduced with permission [139]. Copyright 2013, Elsevier. (b) ZnO nanotube pressure sensors for monitoring breathing cycles and pulse dynamics under motion and apnea conditions. Reproduced with permission [141]. Copyright 2021, Springer Nature. (c) Layer-by-layer fabrication of an all-3D-printed cellulose nanocrystal pyro-piezoelectric nanogenerator. (d) Output signals corresponding to normal and rapid breathing states captured by the device in (c). Reproduced with permission [142]. Copyright 2023, American Chemical Society. (e) Schematic of a folded double-layer piezoelectric sensor system with internal shielding and multilayer electrode configuration. Reproduced with permission [143]. Copyright 2023, WILEY-VCH. (f) Nanocomposite fiber-based piezoelectric sensor for real-time monitoring of respiratory and pulse signals. Reproduced with permission [144]. Copyright 2024, American Chemical Society.

MoS_2 has been widely reported to enhance the performance of PVDF-based piezoelectric nanogenerator (PENG) [145, 146]. Hasan et al. [144] developed a wireless piezoelectric sensor by embedding MoS_2 into PVDF-based fibers. Enhanced interfacial polarization significantly improved the electromechanical conversion efficiency, enabling precise cardiovascular signal prediction when integrated with ML algorithms (**Fig. 8f**). Integrating AI with flexible sensors has also emerged as a research focus to improve data processing accuracy and efficiency. Ahmad et al. [147] proposed an innovative wearable system that enables real-time coupling analysis of HR and RR, offering novel solutions for personalized health management. These advances highlight the transition of HRV and RR-based monitoring technologies from single-function detection to complex multi-parameter analysis, paving the way for future health monitoring and management applications.

Several advanced devices utilizing piezoelectric sensors are already commercially available. EarlySense (an Israeli medical device company) has developed an under-mattress system that detects mechanical vibrations from cardiac and respiratory activity, transmitting real-time data for centralized monitoring and alerting. Clinical studies by Harvard Medical School involving 7,643 patients have shown that this system significantly reduces hospital stays, emergency interventions, and postoperative ICU durations [148]. Similarly, companies like Sensiotec in the U.S. and Emfit in Europe have developed comparable non-contact sensor solutions. The Emfit QS system is the world’s first non-contact sleep monitoring device with HRV monitoring functionality [149, 150]. These products provide new possibilities for noninvasive monitoring technologies in healthcare, demonstrating broad prospects for clinical applications.

3.4 Cardiac function evaluation through multimodal fusion

Cardiac function monitoring plays a critical role in the prevention, diagnosis, and management of cardiovascular diseases. While ECG remains the clinical gold standard for assessing cardiac electrical activity [151, 152], increasing attention has been directed toward integrating complementary sensing modalities to achieve more comprehensive cardiac evaluation. Piezoelectric sensing technology offers a highly sensitive and portable alternative for ECG monitoring. By leveraging the direct piezoelectric effect, these sensors can non-invasively capture mechanical signals associated with cardiac activity—such as micro-vibrations or thoracic deformations—which are temporally correlated with electrocardiographic events, thereby enabling indirect assessment or fusion with ECG signals [153].

Recent studies have demonstrated the effectiveness of integrating piezoelectric sensors with ECG signals for multimodal cardiac monitoring. Cinquino et al. [154] developed a flexible, biocompatible AlN piezoelectric sensor capable of recording pressure waveforms from multiple arterial sites. By synchronizing these piezoelectric signals with ECG, they extracted various cardiovascular indicators—including PWV, SI, and cardio-ankle vascular index (CAVI)—to assess both central and peripheral arterial stiffness (**Fig. 9a**). Similarly, Kim et al. [155] designed a self-powered wearable piezoelectric sensor with micropyramid structures, which combined pulse signals and ECG to estimate PTT and PWV, enabling accurate systolic blood pressure (SBP) monitoring (**Fig. 9b**). These works highlight the potential of multimodal piezoelectric sensing systems for accurate, noninvasive, and continuous cardiac function monitoring in wearable applications.

Moreover, Mokhtari et al. [156] developed a lightweight, Bluetooth-based piezoelectric system for real-time heart monitoring. By aligning piezoelectric signals with ECG data, they extracted key cardiac parameters and used cross-correlation to detect abnormalities (**Fig. 9c**). This method enables accurate, low-power monitoring and classification of cardiac events. Luo et al. [157] developed a flexible nano-cardiac sensor based on a P(VDF-TrFE)/KNN/GR composite film (**Fig. 9d**), significantly improving sensitivity and accuracy in cardiac disease diagnosis. By leveraging the high dielectric constant of KNN, the high conductivity of graphene, and the excellent piezoelectric properties of P(VDF-TrFE), the sensor successfully captures weak heart sound signals. When combined with the RepMLP classification model, the sensor's high sensitivity complements the model's precise classification capabilities, facilitating heartbeat collection and real-time automatic diagnosis and offering new possibilities for early clinical monitoring (**Fig. 9e**).

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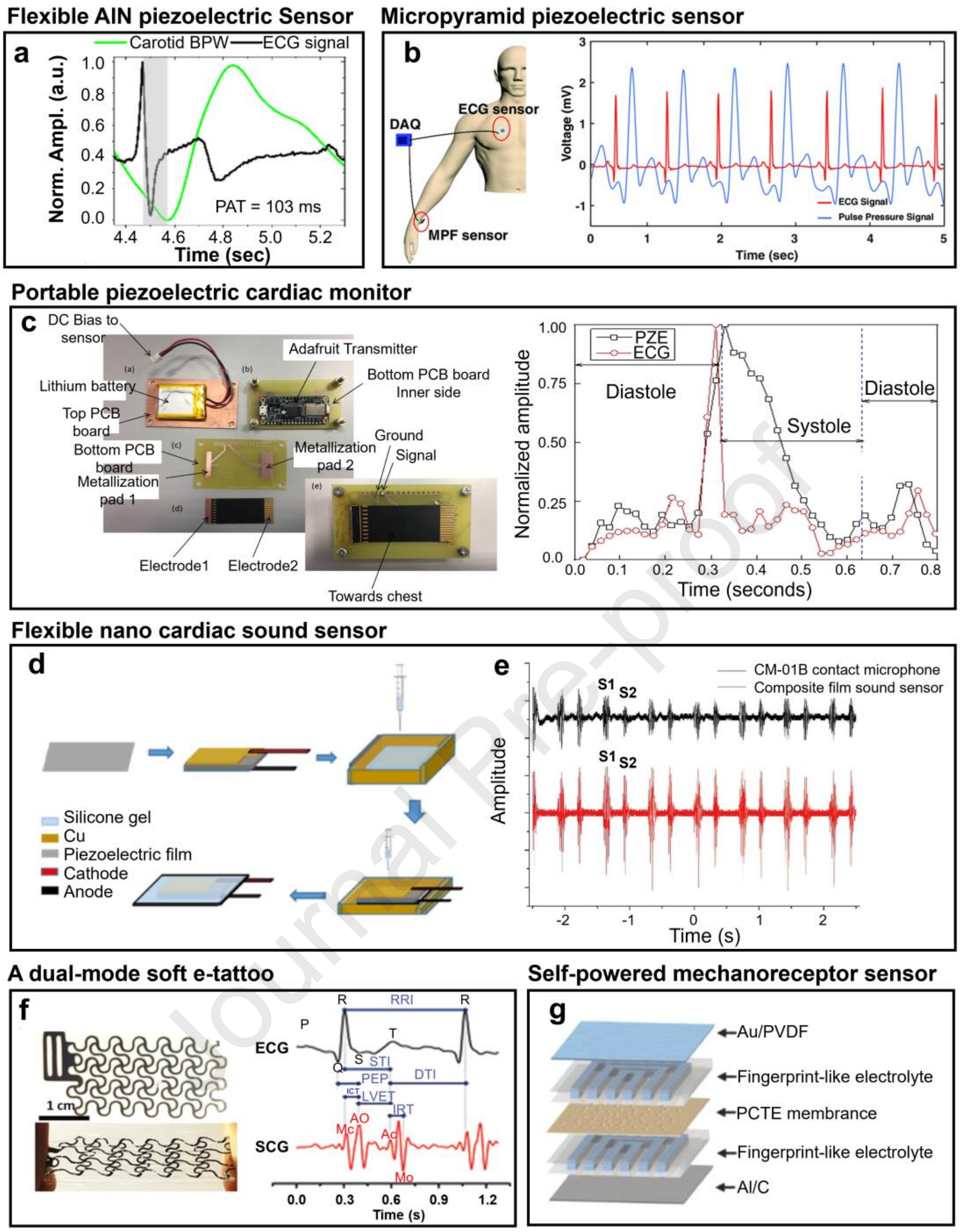

Fig. 9. Multimodal piezoelectric sensors for integrated cardiac function assessment. (a) Simultaneous measurement of carotid pulse pressure and ECG signals for PWV estimation using a flexible AlN-based piezoelectric sensor. Reproduced with permission [154]. Copyright 2025, Elsevier. (b) Concurrent acquisition of pulse and ECG waveforms using a micropyramid-structured piezoelectric sensor. Reproduced with permission [155]. Copyright 2022, WILEY-VCH. (c) Portable cardiac monitoring system integrating piezoelectric sensing, signal acquisition, and wireless transmission, with synchronized ECG and piezoelectric cycle comparison. Reproduced with permission [156]. Copyright 2019, Elsevier. (d–e) Design and performance of a flexible nanocomposite cardiac sound sensor, showing the fabrication process and heart sound signals compared with a standard contact microphone. Reproduced with permission

[157]. Copyright 2023, IOP Publishing. (f) Dual-mode soft e-tattoo platform enabling simultaneous detection of ECG and seismocardiography (SCG), with annotated cardiac time intervals. Reproduced with permission [65]. Copyright 2019, WILEY-VCH. (g) Schematic of a self-powered mechanoreceptor sensor with a fingerprint-mimicking multilayer structure. Reproduced with permission [158]. Copyright 2018, WILEY-VCH.

More and more researchers are developing PVDF-based stretchable electromechanical sensors based on micropatterned PVDF membrane [159], ribbon-like PVDF embedded in Ecoflex [160], and PVDF islands interconnected by serpentine metal wires [161] on PVDF-based stretchable electromechanical sensors. Ha et al. [65] developed a soft, stretchable e-tattoo that integrates piezoelectric and ECG sensors for synchronous recording of SCG and ECG signals (**Fig. 9f**). This fusion enables the extraction of detailed cardiac time intervals, such as the systolic time interval (STI), which shows a strong negative correlation with BP. By aligning mechanical and electrical signals on a single skin-conformal device, the study demonstrates a low-profile, wearable solution for continuous, noninvasive cardiovascular monitoring. Chun et al. [158] developed a self-powered mechanoreceptor-inspired sensor that mimics the fast- and slow-adapting responses of human skin by combining a piezoelectric PVDF film with an ion-channel-based layer (**Fig. 9g**). Instead of pursuing fusion with ECG signals, like previous studies, this work achieves signal integration at the material level, using the piezoelectric layer to detect dynamic pulses and the ionic component for static pressure. This dual-mode sensing enables real-time monitoring of pulse waves, BCG, and tactile stimuli, offering a bioinspired, low-power approach to cardiovascular and sensory signal tracking.

In addition to electro-mechanical fusion, recent efforts have explored the integration of piezoelectric sensors with optical signals, particularly PPG, to enable complementary cardiovascular assessment. Jin et al. [162] developed a flexible optoacoustic platform that couples PVDF-based piezoelectric receivers with microlens arrays, allowing multiparametric evaluation of vascular dynamics, blood oxygenation, and endothelial function through light-induced acoustic signals. Deng et al. [163] introduced a fully wearable tonometric system combining piezoelectric pressure arrays with optical sensors and adaptive mechanical control for real-time, medical-grade hemodynamic monitoring. Samartkit et al. [164] further demonstrated that combining PZT sensors with PPG enables pulse transit time estimation through a modified algorithm, supporting accurate, low-power BP tracking in ambulatory settings. These multimodal strategies highlight the central role of piezoelectric sensing in enabling continuous, high-resolution, and integrative cardiac function monitoring across electrical, mechanical, and optical domains.

3.5 Intelligent monitoring systems

3.5.1 AI-driven signal interpretation

The integration of AI has significantly enhanced the performance of cardiovascular monitoring systems by improving data processing accuracy and enabling multimodal analysis [165]. Combined with advanced piezoelectric sensors and DL algorithms, these systems support early disease detection, personalized health management, and continuous noninvasive monitoring, offering broad clinical and daily healthcare applications [166, 167]. Several studies have demonstrated the effectiveness of AI-based approaches. Ahmadpour et al. [168] introduced a piezoelectric metamaterial BP sensor, employing Bayesian optimization and ML regression models to identify optimal design parameters. Wang et al. [169] developed a piezoelectric system for continuous BP estimation based on initial values and pressure accumulation, achieving a mean absolute error under 5 mmHg and a standard deviation below 8 mmHg. To address the needs of maternal health monitoring, Nie et al. [170] integrated a piezoelectric thin-film pulse sensor with modal energy ratio (MER) analysis based on EMD. The system successfully analyzed data from 83 pregnant participants, enabling early identification of health risks and pregnancy-related indicators.

Accurately tracking arterial mechanical properties, which vary significantly between individuals and can change over time due to external stimuli, poses a formidable challenge for understanding their impact on BP fluctuations. Recurrent neural networks (RNNs) effectively account for the dynamic variability of arterial characteristics, thereby enhancing the stability of long-term models (**Fig. 10a**). Additionally, combining pulse features with propagation characteristics, such as PAT and PTT, further improves model accuracy and long-term reliability [171] (**Fig. 10b**). Sun et al. [172] developed an intelligent cardiovascular disease diagnosis system integrating a 2D Bi_2O_2Se PENG with DL technology. This system combines self-powered pulse sensors with DL models to accurately identify nine common cardiovascular diseases (**Fig. 10c**). Huang et al. [173] developed a BP monitoring system based on a flexible piezoelectric sensor made from PVDF and MXene composites. The sensor is integrated with a DL model (MLSU-net) that predicts BP waveforms using PPG signals, incorporating multi-scale convolutional kernels and long short-term memory (LSTM) networks. This system enables real-time BP estimation using a single-channel signal, overcoming data filtering issues and improving prediction accuracy (**Fig. 10d**). Karin et al. [174] demonstrated a customized sensor integrated into a chair, enabling non-contact monitoring where arterial vibrations modulate pressure applied to the sensor. A deep neural network model exhibited significant potential for personalized identification of abnormal biosignals in individuals (**Fig. 10e**).

Cao et al. [175] developed an intelligent atrial fibrillation (AF) recognition system that integrates AI with the traditional Chinese medicine (TCM) concept of pulse diagnosis. A wearable, flexible three-dimensional pressure sensor array was employed to collect pulse signals from the Cun, Guan, and Chi positions, which were then analyzed using a convolutional neural network (CNN) to accurately distinguish between healthy and AF pulse patterns, achieving a recognition accuracy of 93.2% (**Fig. 10f**). Similarly, Chu et al. [176] designed an aortic pulse sensing system based on a sandwich-structured piezoelectric material (FEP/Ecoflex/FEP). By leveraging ML-based big data analysis, the system enabled precise identification and classification of individual pulse waveforms (**Fig. 10g**). This sensing platform allows for continuous HR monitoring, arrhythmia detection, and BP estimation, offering a high-precision, noninvasive, AI-assisted solution for cardiovascular health monitoring in mobile healthcare settings.

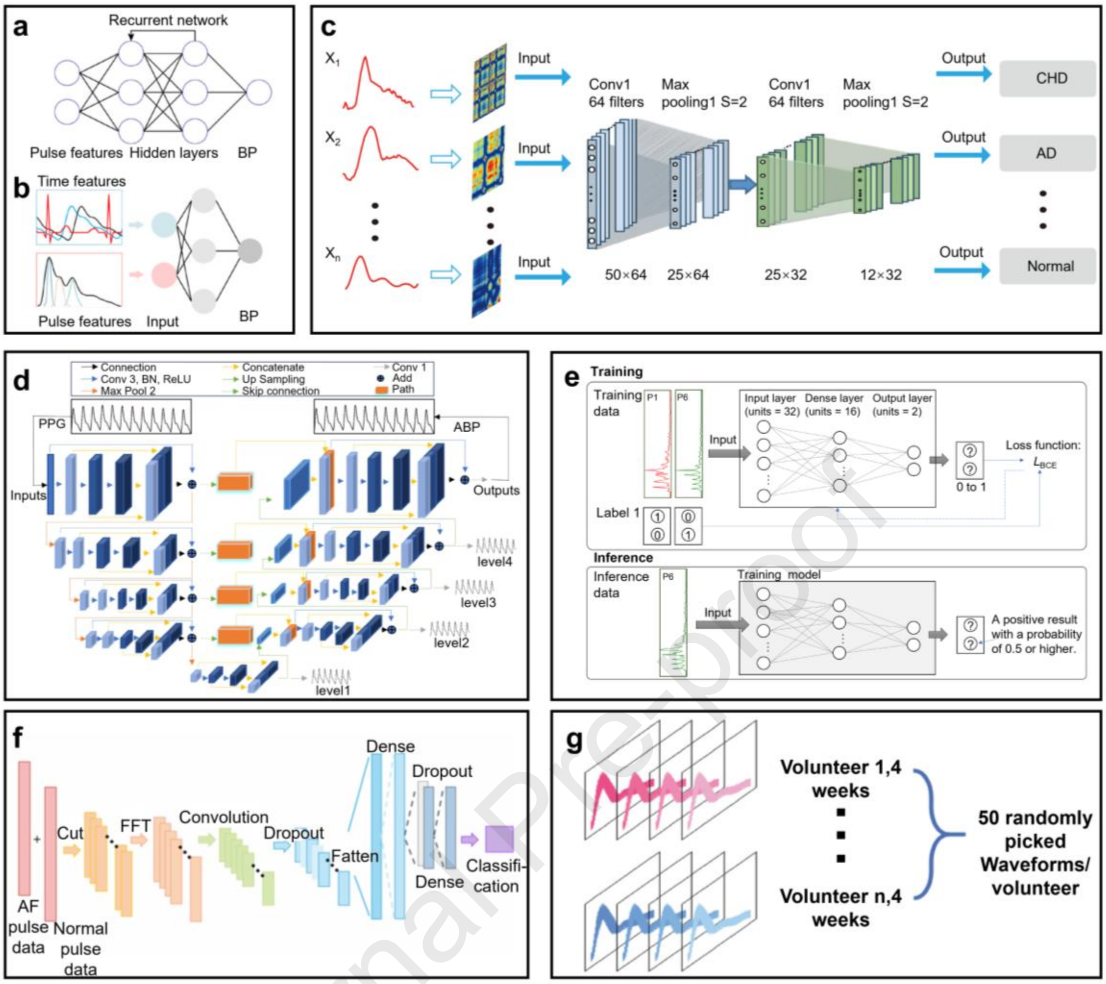

Fig. 10. AI-enabled analysis of piezoelectric pulse signals for cardiovascular health monitoring. (a) RNN model for extracting temporal features from pulse signals to estimate BP. (b) Multifactor model integrating time-domain and morphological features for enhanced BP prediction. Reproduced with permission [171]. Copyright 2024, American Chemical Society. (c) CNN-based classification of cardiovascular disease status using piezoelectric pulse data. Reproduced with permission [172]. Copyright 2024, Elsevier. (d) Architecture of a multi-level supervised network mapping PPG to arterial blood pressure (ABP). Reproduced with permission [173]. Copyright 2025, Elsevier. (e) Workflow of model training and inference using pulse waveform data. Reproduced with permission [174]. Copyright 2024, MDPI. (f) CNN framework for arrhythmia classification based on pulse waveform transformation and feature extraction. Reproduced with permission [175]. Copyright 2025, American Chemical Society. (g) Schematic of the pulse pattern clustering process across volunteers for waveform discrimination and population-based analysis. Reproduced with permission [176]. Copyright 2018, WILEY-VCH.

3.5.2 IoT-enabled remote connectivity

The IoT has emerged as a transformative force in digital healthcare, supporting continuous, real-time, and remote monitoring of physiological parameters. Typically composed of four components—smart sensors, cloud computing, wireless networks, and analytical software [177]—IoT-enabled cardiovascular systems rely on wireless technologies such as Bluetooth Low Energy (BLE), Wi-Fi, Near-field communication (NFC), and cellular networks to transmit physiological data from sensors to mobile or cloud-based platforms for further analysis and clinical decision-making. Babu et al. [178] developed a highly sensitive flexible piezoelectric sensor for arterial pulse wave recording and cardiovascular health assessment (**Fig. 11a**). The system integrated a system-on-chip (SoC) for wireless data transmission, enabling real-time pulse signal delivery to remote devices and facilitating early prediction of cardiovascular abnormalities with an accuracy exceeding 94%. In another example, Hesar et al. [179] engineered a flexible, battery-free epidermal electronic system (EES) with integrated ECG and SCG sensors to simultaneously acquire electrical and mechanical cardiac signals (**Fig. 11b**). This system utilized NFC technology for wireless power and data transfer, combined with automatic signal analysis and health state recognition, and successfully identified cases of cardiopulmonary hypertension.

Park et al. [63] developed a self-feeding flexible piezoelectric pulse sensor based on an ultrathin PZT film, capable of conformally adhering to human skin for high-sensitivity, real-time monitoring of radial and carotid pulse waves (**Fig. 11c**). The sensor system incorporated a microcontroller unit (MCU) and BLE module to wirelessly transmit data to smartphones, while also supporting real-time feedback via integrated LEDs and acoustic alerts. Similarly, a kirigami-inspired flexible piezoelectric sensor system was developed by Sun et al. [180], featuring excellent skin conformity and energy autonomy. The system, equipped with an NFC module, enabled stable, battery-free wireless data transmission, providing a compact and low-power IoT solution for wearable and implantable cardiovascular monitoring (**Fig. 11d**). Kar et al. [181] developed a novel composite piezoelectric material by repurposing chicken feathers into processable chicken feather fibers (CFF) and incorporating them as fillers into PVDF (**Fig. 11e**). The device enabled remote real-time monitoring via Wi-Fi connectivity and was used for monitoring various physiological signals, including body motion, throat activity, and pulse rate, exhibiting excellent sensitivity and offering broad application in telemedicine and personalized health management.

Existing studies have evaluated the effectiveness of ex vivo sensors in predicting and detecting a wide range of cardiac events. Yu et al. [182] developed a non-contact BCG monitoring system based on piezoelectric ceramics, which was clinically validated overnight in 37 hospitalized patients with sleep apnea syndrome (SAS). The system integrated AI algorithms and embedded data transmission modules, confirming its feasibility for accurate HRV analysis in clinical settings. Lin et al. [183] further proposed a BLE-enabled, wireless multi-lead polysomnography (PSG) system for sleep monitoring, capable of real-time transmission of multichannel physiological data. Comparative clinical tests with the standard Alice 5 PSG system showed a high degree of agreement in sleep stage recognition, supporting the feasibility of this IoT-based system for low-power, continuous cardiopulmonary monitoring in home environments. These studies have fueled the emergence of FDA-approved noninvasive cardiac monitoring systems that promise to aid in the diagnosis of multiple HRV-related syndromes [184].

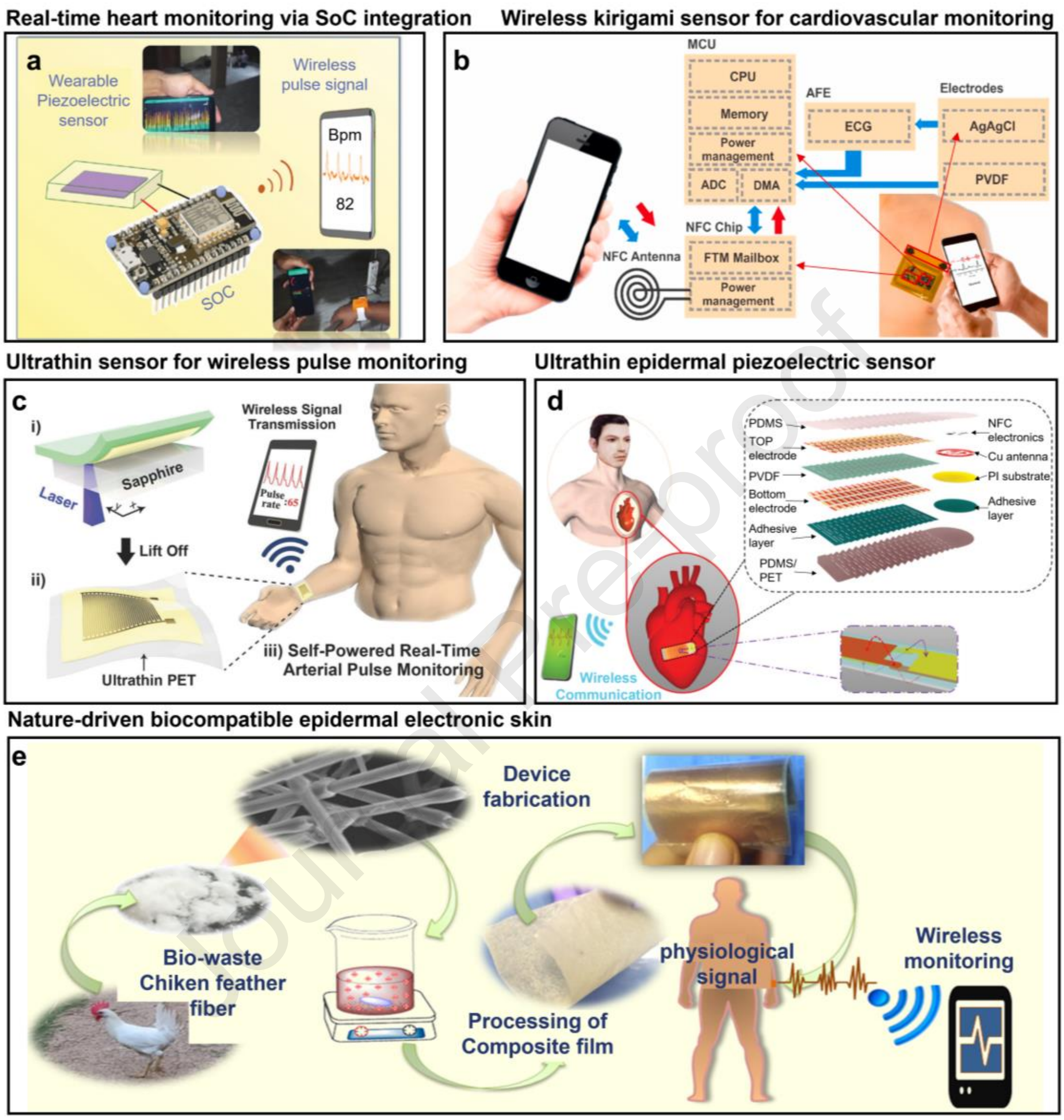

Fig. 11. IoT-integrated piezoelectric platforms for wireless cardiovascular health monitoring. (a) Real-time arterial pulse sensing and wireless data transmission using a piezoelectric sensor integrated with a SoC platform. Reproduced with permission [178]. Copyright 2023, WILEY-VCH. (b) Schematic of an electronic epidermal system (EES) comprising power, signal processing, and ECG modules with NFC-enabled wireless communication. Reproduced with permission [179]. Copyright 2023, Elsevier. (c) Fabrication and application of an ultrathin self-powered piezoelectric sensor for real-time arterial pulse monitoring, based on transferred PZT films on PET substrates. Reproduced with permission [63]. Copyright 2017, WILEY-VCH. (d) Integrated multilayer piezoelectric sensor and wireless patch for epidermal cardiovascular monitoring, with details of component architecture and electrode patterning. Reproduced with permission [180]. Copyright 2019, WILEY-VCH. (e) Development

of a nature-derived organohydrogel-based epidermal electronic skin from chicken feather waste, enabling biocompatible signal acquisition and smartphone-based wireless monitoring. Reproduced with permission [181]. Copyright 2019, American Chemical Society.

3.6 Comparative evaluation of sensing technologies

Although piezoelectric technology offers numerous advantages in cardiovascular health monitoring, including high sensitivity, the absence of external power requirements, and exceptional flexibility, it also has certain limitations. For instance, some sensors exhibit relatively slow response times or insufficient stability under long-term cyclic loading, which may limit their effectiveness in continuous monitoring applications. These challenges are often caused by variations in the choice of sensitive materials and structural designs, resulting in significant differences in sensing performance. As summarized in **Table 3**, a variety of flexible piezoelectric sensors have been developed for cardiovascular health monitoring, addressing parameters such as arterial health, cuffless blood pressure, and multiparametric cardiopulmonary signals. These sensors exhibit substantial variability in sensitivity, response time, and operational stability, depending on the materials, structural configurations, and sensing mechanisms employed.

Overall, piezoelectric technology is rapidly advancing in the field of cardiovascular health monitoring, providing an effective means to enhance the prevention, diagnosis, and treatment of cardiovascular diseases. With further research and technological progress, the development of more efficient and accurate piezoelectric monitoring devices is anticipated, promising revolutionary improvements in cardiovascular health management.

4 Challenges and outlook

4.1 Technical and clinical challenges

Although piezoelectric technology exhibits tremendous potential in cardiovascular health monitoring, it also faces a range of challenges. Below is a detailed discussion of these challenges and corresponding strategies to address them (**Fig. 12**).

Fig. 12. Challenges and outlook for piezoelectric technologies in cardiovascular health monitoring. This figure outlines the primary challenges, such as packaging and degradability, biocompatibility, long-term stability, sensitivity, and accuracy, alongside promising prospects, including material innovation, signal acquisition, wireless transmission, device miniaturization, and AI integration. Emerging directions feature

the use of Janus materials, transition-metal dichalcogenides (TMDs), conformal device integration, and AI-driven data analysis for personalized cardiovascular health management. Reproduced with permission [185]. Copyright 2023, WILEY-VCH. Reproduced with permission [186]. Copyright 2020, ROYAL SOCIETY OF CHEMISTRY.

(1) Monitoring accuracy and sensitivity

Achieving high accuracy and sensitivity remains a critical challenge for piezoelectric sensors in cardiovascular monitoring, where subtle physiological changes often carry significant clinical value. However, signal quality can be compromised by environmental noise, electromagnetic interference, and limitations in material or structural design. Recent advances in materials science, such as PVDF composites with carbon nanotubes or conductive polymers, have enhanced signal transduction, flexibility, and biocompatibility [187-191]. Multilayer structures and nanocomposites further amplify weak bio-signals by increasing effective piezoelectric output and optimizing stress distribution. Representative efforts include folded-structure electret sensors for low-frequency non-contact sensing [192] and ML algorithms-assisted microstructure optimization to boost material sensitivity and stability [193]. The convergence of materials innovation, structural engineering, and intelligent analytics is essential for overcoming current performance limitations and advancing toward reliable, high-precision, and multifunctional piezoelectric health monitoring systems.

(2) Packaging and biodegradability

For implantable piezoelectric devices, ensuring both long-term stability and biological safety requires careful consideration of material biodegradability and packaging strategies. Biodegradable piezoelectric materials, often derived from natural

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polymers or bioresorbable composites, can safely degrade after completing their monitoring tasks, reducing chronic tissue responses and postoperative complications [194-199]. However, their mechanical and electrical performance may be inferior to non-degradable counterparts, necessitating structural optimization and surface modifications to enhance durability and compatibility [200-202]. Meanwhile, packaging is essential for isolating sensors from biological fluids and maintaining functional integrity. Flexible polymers such as PDMS and PLGA are widely used due to their biocompatibility and barrier properties [203, 204]. Advanced transient systems combine biodegradable substrates with multilayer encapsulants—such as waxes or polyanhydrides—to tune operational lifespan from hours to weeks, depending on the clinical need [205-207]. These co-engineered approaches to material degradation and protective encapsulation are crucial for enabling safe, effective, and temporally controlled operation of next-generation implantable piezoelectric sensors.

(3) Biocompatibility and durability

Ensuring biocompatibility and durability is fundamental to the long-term functionality of piezoelectric sensors in physiological environments. Poor material compatibility can trigger immune responses or inflammation, while insufficient durability — due to mechanical fatigue, chemical corrosion, or environmental degradation—may lead to signal instability, especially in flexible devices under repeated deformation. Traditional materials like PZT and $BaTiO_3$ often present toxicity risks, whereas biocompatible alternatives such as PVDF and ZnO offer safer interactions with tissue and are now widely adopted in implantable systems [208-211].

To further improve biological integration, surface engineering techniques and biodegradable materials have been employed, minimizing adverse immune responses and reducing post-implantation complications [212-215]. Simultaneously, durability is reinforced through the use of high-strength composites, flexible nanocomposites, and protective barrier coatings—such as polymer or ceramic encapsulants—which enhance resistance to mechanical and chemical stress [216-218]. These material and structural strategies collectively improve the safety, stability, and lifespan of piezoelectric devices, supporting their reliable operation in complex and dynamic in vivo conditions.

(4) Data processing and privacy protection

Cardiovascular monitoring generates large volumes of data requiring real-time processing, high accuracy, and robust privacy safeguards. Cloud and edge computing architectures help address these needs: cloud platforms support large-scale analysis, while edge computing reduces latency by enabling local signal processing [219-222]. Emerging frameworks combining blockchain and federated learning enable decentralized cardiovascular data analysis while preserving data ownership and integrity [223]. ML methods, including support vector machines and deep neural networks, enhance feature extraction and anomaly detection [224, 225]. To secure sensitive health data, encryption protocols, differential privacy, and blockchain-based access control have been widely adopted [226]. These technologies help prevent unauthorized access and foster trust in wearable and implantable piezoelectric monitoring systems.

4.2 Outlook and conclusion

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Piezoelectric technology is transforming cardiovascular health monitoring by offering high sensitivity, rapid response, and inherent self-powered functionality. These attributes enable the real-time detection of subtle biomechanical signals such as arterial pulsations, cardiac microvibrations, and BP variations, supporting continuous, noninvasive, and high-fidelity monitoring across both wearable and implantable formats. The ability to operate without external power sources also facilitates long-term and sustainable physiological tracking.

To achieve clinical translation, several challenges must be addressed. The development of lead-free, biodegradable, and intrinsically flexible piezoelectric materials is essential to ensure both biocompatibility and safety, particularly in implantable settings. At the same time, device encapsulation plays a critical role. For biodegradable systems, packaging materials must preserve signal fidelity and mechanical integrity while exhibiting predictable and bio-safe degradation behavior. In addition, the design of the device–tissue interface must support stable performance and intimate contact under dynamically changing physiological conditions.

Reliable wireless data transmission is another key requirement. For implantable systems, wired communication is neither practical nor clinically feasible. Therefore, compact and efficient wireless communication modules such as Bluetooth, near-field communication, or radiofrequency backscatter-based systems are necessary to enable real-time physiological monitoring. Passive wireless platforms based on radiofrequency mechanisms are particularly promising. For instance, chipless electronic skins incorporating surface acoustic wave sensors made from ultrathin gallium nitride membranes have demonstrated high-sensitivity, battery-free monitoring of physiological parameters, including strain, ultraviolet exposure, and pulse. These technologies offer a viable pathway toward minimally invasive, long-term wearable and implantable monitoring platforms.

Piezoelectric systems also enable multidimensional cardiovascular monitoring through two complementary modalities. The first involves the integration of diverse mechanical signals, including pulse waveforms, heart sounds, cardiac microvibrations, and arterial pressure changes, into a single sensing unit, providing comprehensive assessments of cardiac function. The second modality leverages the high sensitivity of surface acoustic wave sensors to changes in mechanical, chemical, and optical environments, allowing for the detection of ionic concentrations, biochemical reactions, and light-triggered responses. Together, these approaches facilitate the development of compact and integrated systems capable of delivering high-resolution and personalized cardiovascular diagnostics.

The incorporation of AI and edge computing further extends the potential of piezoelectric sensing systems. These technologies enable real-time anomaly detection, continuous risk assessment, and automated clinical decision-making. Concurrently, the integration of IoT infrastructure supports remote monitoring and decentralized healthcare delivery, expanding access to continuous cardiovascular diagnostics. Among the emerging innovations, bioresorbable piezoelectric devices are particularly promising for postoperative monitoring and use in high-risk patient populations. These temporary devices provide short-term functionality and degrade safely in vivo,

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eliminating the need for surgical retrieval.

In summary, piezoelectric technology is positioned to become a foundational component of next-generation cardiovascular diagnostic and therapeutic systems. Continued advances in material development, device encapsulation, wireless communication, and intelligent data analytics will be essential for realizing clinically practical, high-performance platforms that seamlessly connect real-time physiological monitoring with precision medical interventions.

Competing financial interests

The authors declare no competing financial interests.

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Table 1. Comparative evaluation of cardiovascular monitoring technologies

Technology	Representative materials	Sensitivity	Accuracy	Cost	Ease of use	Power consumption	Applications
Piezoelectric	PVDF, PZT, quartz	($6.3E^{-7}$–10) $V{\cdot}Pa^{-1}$ [73, 227]	98.3% [93]	Cost-effective	Flexible, wearable, high comfort	Self-powered	BP, SCG, Korotkoff sounds, Multimodal monitoring
Piezoresistive	Carbon black, rGO, PEDOT:PSS	(0.66–284.4) kPa^{-1} [228, 229]	96.03% [230]	Cost-effective	Flexible, wearable, high comfort	3nW/ Low [230]	HR, RR
Capacitive	PDMS, PU, metal	(0.148–56.91) kPa^{-1} [231, 232]	91.2% [233]	Cost-effective	Flexible, wearable, high comfort	7.8 mW/ Mid [234]	HR, RR
PPG	OLED, OPD	3.5×10^5 A W^{-1} [13]	99.5% [235]	$24–210 Medium-cost	Rigid, wearable, moderate comfort	1.66 mW/ Mid [236]	HR, BP, SpO_2
Traditional ECG	Ag/AgCl	>96%* [237]	>99% [237]	$288–2302 High-cost	Rigid, non-portable, low comfort	16.4–373.2 mW/ High [238]	ECG, HRV, Arrhythmia classification
Holter	Ag/AgCl	>99%* [239]	> 99% [240]	$206–4111 High-cost	Rigid, wearable, moderate comfort	>100 mW/ High [241]	Long-term ECG, AF, HRV

* QRS wave recognition rate

1041 **Table 2. Advantages and limitations of various piezoelectric materials**

Type of material	Advantages	Limitations	Applications
0D material	▲High surface energy ▲Excellent charge coupling ▲Easy to integrate into composites	■Low mechanical strength ■Limited structural stability ■Hard to scale	★Microscale sensors ★Material optimization ★Nanogenerators
1D materials	▲High aspect ratio ▲Strong directional response ▲Flexible and lightweight	■Difficult manufacturing process ■Lower bulk stability ■Limited long-term durability	★Wearable devices ★Blood pressure sensors ★Implantable monitors
2D materials	▲Planar structure with anisotropic properties ▲Strong piezoelectric effect ▲Flexible	■Mechanical durability under cyclic loads ■Limited large-scale integration ■Moderate thermal stability	★Flexible electronics ★Cardiac motion monitoring ★Multi-modal sensors
3D materials	▲High mechanical stability ▲Strong bulk piezoelectricity ▲Adaptable to complex geometries	■Rigid and inflexible ■Relatively heavy ■Requires advanced processing for flexibility	★Ultrasound imaging ★Energy harvesting ★Implantable cardiovascular devices

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Table 3. **Flexible piezoelectric sensors for monitoring CVD-related parameters**: **materials, principle of operation, and performance**

	Mechanism	Sensitive materials	Structure	Sensitivity	Response time	Stability
Arterial health assessment	Piezoelectric	PVDF	Membrane [68]	173 mV/mmHg	30 ms	Number of cycles >50,000
	Piezoelectric	P(VDF-TrFE)	Membrane [73]	0.63 $\mu V \cdot Pa^{-1}$	-	Number of cycles >400,000
	Piezoelectric	PVDF/DA	Core–shell structure [86]	-59.4 $pm \cdot V^{-1}$	-	Number of cycles >2,000
	Piezoelectric	PVDF	Organohydrogels [242]	1.34 $mV \cdot kPa^{-1}$	31 ms	Number of cycles >5,000
	Piezoelectric	$BaTiO_3$	Micropyramid balloon catheter [72]	19.12 $mV \cdot kPa^{-1}$	-	-
	Piezoelectric	PVDF/HFP	Zigzag-shaped piezoelectric stent [69]	7.02×10^{-4} $V \cdot Psi^{-1}$	-	Number of cycles >10,000
	Piezoelectric	PVDF/CFF	Electronic skin [181]	93 $mV \cdot kPa^{-1}$	0.88 ms	>7 weeks
	Piezoelectric/Capacitor	GaN	E-skin [66]	10.06 $A \cdot W^{-1}$	-	Number of cycles >3,000
Cuffless blood pressure estimation	Piezoelectric	PZT	Piezoelectric thin film [94]	0.062 kPa^{-1}	23 ms	Number of cycles >50,000
	Piezoelectric	PZT	Porous nanocomposite films [96]	9.07 $mV \cdot kPa^{-1}$	50 ms	Number of cycles >20,000
	Piezoelectric	BN/PT & MXene/PT	Heterogeneously hierarchical piezoelectric composite [97]	39.3 $mV \cdot kPa^{-1}$	30.1 ms	>30 days
	Piezoresistive/Piezoelectric	Polypropylene	Membrane [243]	600 $pC \cdot N^{-1}$	-	-
Multiparametric cardiopulmonary monitoring	Piezoelectric	PVDF	Curved structure [138]	0.153 V/strain%	-	-
	Piezoelectric	ZnO nanotube/graphene	ZnO nanotube arrays [141]	-4.4 kPa^{-1}	<100 ms	Number of cycles >18,000
	Pyro-piezoelectric	Cellulose nanocrystal	Multilayer structure [142]	0.8 $V \cdot kPa^{-1}$	8 ms	Number of cycles >1,000
	Piezoelectric	PZT	Electronic skin [63]	0.018 kPa^{-1}	60 ms	Number of cycles >5,000
	Piezoelectric	FEP	Folded double-layer piezoelectric sensor [143]	3.33 $V \cdot kPa^{-1}$	-	Number of cycles >1,100,000
	Piezoelectric	MoS_2/PVDF	Nanocomposite fiber sensors [144]	0.22 $V \cdot kPa^{-1}$	-	>6 weeks
Multimodal signal fusion	Piezoelectric-like	FEP	Sandwich-structure piezoelectric [176]	4100 $pC \cdot N^{-1}$	18.6 ms	Number of cycles >3,600
	Piezoelectric/Ion channel	PVDF/PCTE	Membrane [158]	0.21 $V \cdot kPa^{-1}$	20 ms	>10,000 s
	Piezoelectric	PVDF	Filamentary serpentine mesh [65]	0.4 $mV \cdot \mu\varepsilon^{-1}$	-	Number of cycles >10,000
	Piezoelectric	P(VDF-TrFE)/KNN/GR	Composite piezoelectric thin film [157]	430.6 $pC \cdot N^{-1}$	-	Number of cycles >2,800

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2. Integration of piezoelectric sensors with AI and IoT for intelligent diagnostics.

3. Advances in wearable and implantable piezoelectric devices for real-time sensing.

4. Challenges and future directions for material design, encapsulation, and clinical translation.

Declaration of Interest Statement

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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