Review

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Self-powered cardiovascular medical devices

From monitoring to therapy

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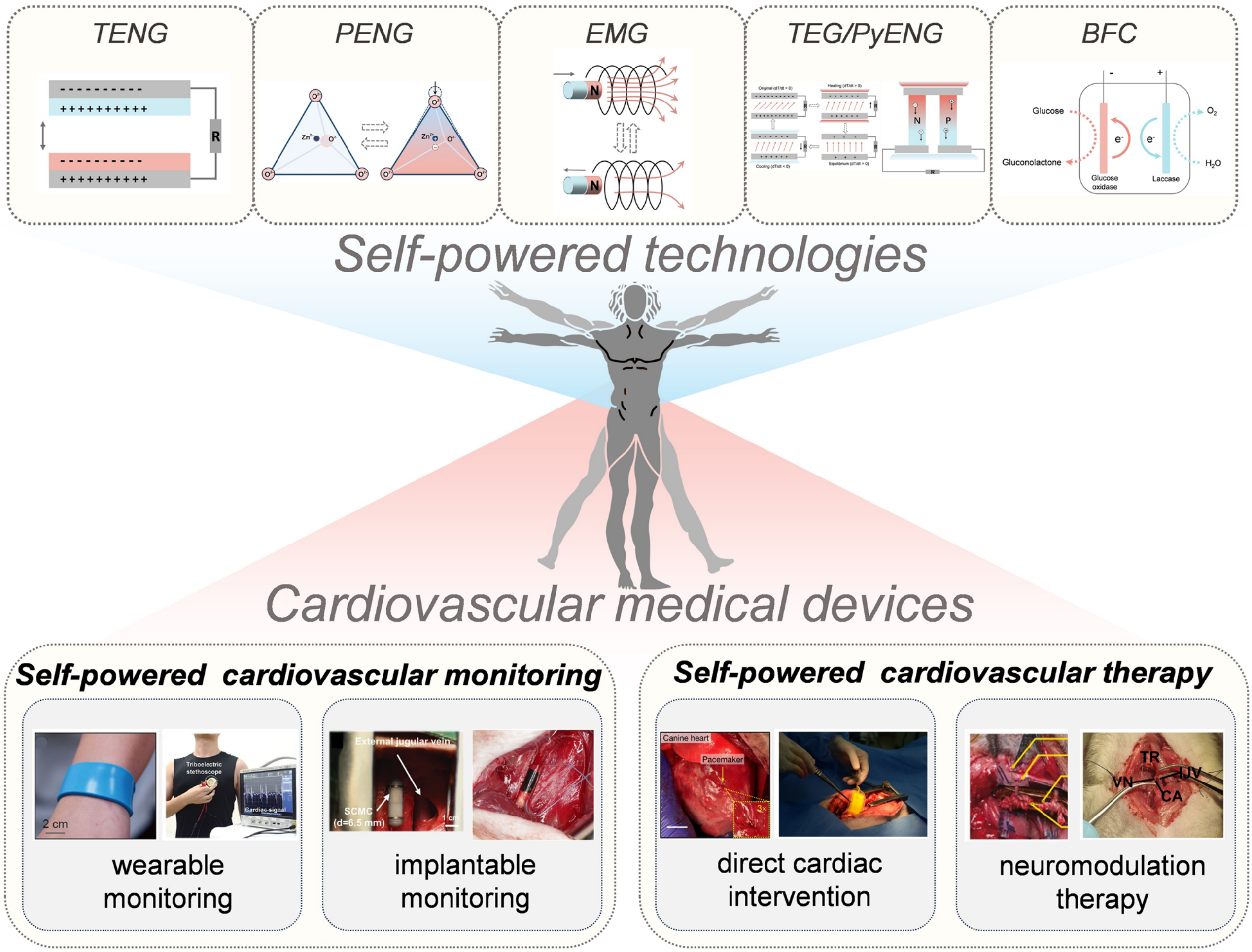
Graphical abstract



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ABSTRACT
Cardiovascular disease remains the leading cause of death worldwide, and diseases such as arrhythmias, heart failure, and coronary heart disease pose significant challenges to diagnosis and treatment due to their high morbidity, sudden onset, and frequent complications. Traditional cardiovascular disease management often relies on clinical diagnosis and complex, bulky, and large monitoring devices, which limit their lifespan, portability, and long-term applicability. In recent years, self-powered technologies have developed rapidly, and they have opened up new avenues for cardiovascular health care by enabling power-free sensing and harvesting energy from physiological activities. These technologies show great potential in developing next-generation cardiovascular medical devices for continuous monitoring and therapeutic intervention. This paper reviews the working mechanisms of various self-powered technologies and systematically summarizes their applications in cardiovascular monitoring and treatment. We particularly emphasize the representative progress of wearable and implantable self-powered cardiovascular monitoring devices, as well as self-powered cardiac intervention therapy devices and neuromodulation therapy devices. Finally, the main challenges and future prospects of this emerging field are discussed, aiming to provide insights and inspiration for further research and clinical application of self-powered cardiovascular medical devices.

Abbreviations: AF = atrial fibrillation, ANS = autonomic nervous system, BCMC = bias-free cardiac monitoring capsule, BFC = biofuel cell, BP = blood pressure, CVDs = cardiovascular diseases, ECG = electrocardiograms, EMG = electromagnetic generator, FCP = fuel cell patch, LL-VNS = low-level vagus nerve stimulation, MI = myocardial infarction, PENG = piezoelectric nanogenerator, PFM = permanent fluid magnet, PPG = photoplethysmography, PyENG = pyroelectric nanogenerators, TEG = thermoelectric generator, TENG = triboelectric nanogenerator, TRI-TENG = trinity TENG-based cardiac patch, VNS = vagus nerve stimulation.

Keywords: cardiovascular medical devices, cardiovascular monitoring, self-powered, therapy

1. Introduction

Cardiovascular diseases (CVDs) are one of the diseases with the highest mortality rate worldwide, causing about 20 million deaths each year, seriously threatening human health.[1] Arrhythmia, heart failure (atrial fibrillation [AF]), and coronary heart disease are common CVDs with high incidence rates. They are often sudden in onset and frequently associated with multiple complications. There is an urgent need to achieve efficient, continuous, and accurate diagnosis and treatment. Traditional CVDs management relies on large and complex equipment in hospitals, such as electrocardiograms (ECGs), dynamic blood pressure (BP) monitors, and Doppler ultrasound, which cannot meet people's needs for portable, long-term, and continuous monitoring. Existing implantable therapeutic devices such as pacemakers and defibrillators usually rely on battery power, which has problems such as limited life, large size, and the need for secondary surgery.[2,3] Therefore, there is a great demand for the research and development of the new generation of cardiovascular monitoring and treatment equipment, which must be achieved through novel materials and design innovations.

In recent years, with the advancement of self-powered technology, it has offered promising alternatives to traditional devices. Self-powered technologies such as triboelectric nanogenerators (TENGs),[4,5] piezoelectric nanogenerators (PENGs),[6,7] fuel cells,[8,9] electromagnetic induction,[10,11] thermoelectric and pyroelectric effect[12,13] are gradually being applied to cardiovascular medical devices. On the one hand, they can be used as physiological signal sensors to achieve self-powered sensing of cardiovascular parameters and provide more accurate, compact, and long-term CVD monitoring. On the other hand, they can collect energy such as human movement, heat, and heartbeat to power wearable and implantable cardiovascular medical devices, so that the equipment can operate for a long time without external batteries, which significantly improves the portability and adaptability of the equipment.

At the application level, self-powered medical devices show broad prospects in cardiovascular monitoring and treatment. For monitoring, self-powered wearables have been applied to real-time detection of physiological signals, including pulse, BP, and heart sounds. These devices are usually flexible, thin, and conformal, and are suitable for long-term use in complex scenarios such as sleep and exercise.[14–18] In contrast, implantable devices have higher detection sensitivity and anti-interference ability due to their direct contact with the heart or arteries, and are suitable for fine monitoring of high-risk patients such as arrhythmias and AF.[19–22] In terms of treatment, the battery life of traditional cardiac intervention treatment devices such as pacemakers has long restricted their development. Self-powered therapeutic devices can harvest energy from heartbeat and blood flow to power treatment modules or deliver electrical stimulation to myocardial tissue, reducing reliance on external power sources, enabling long-term use, and lowering surgical and economic burdens for patients.[23–26] In addition to direct cardiac intervention, neuromodulation therapy has also attracted attention in recent years.[27–29] Vagus nerve stimulation (VNS) has a significant effect on regulating heart rate and BP. Researchers have developed a closed-loop self-powered low-level vagus nerve stimulation (LL-VNS) system, which has a significant effect on the treatment of AF.[30]

In summary, as a new medical technology system integrating energy harvesting, signal sensing, and intelligent

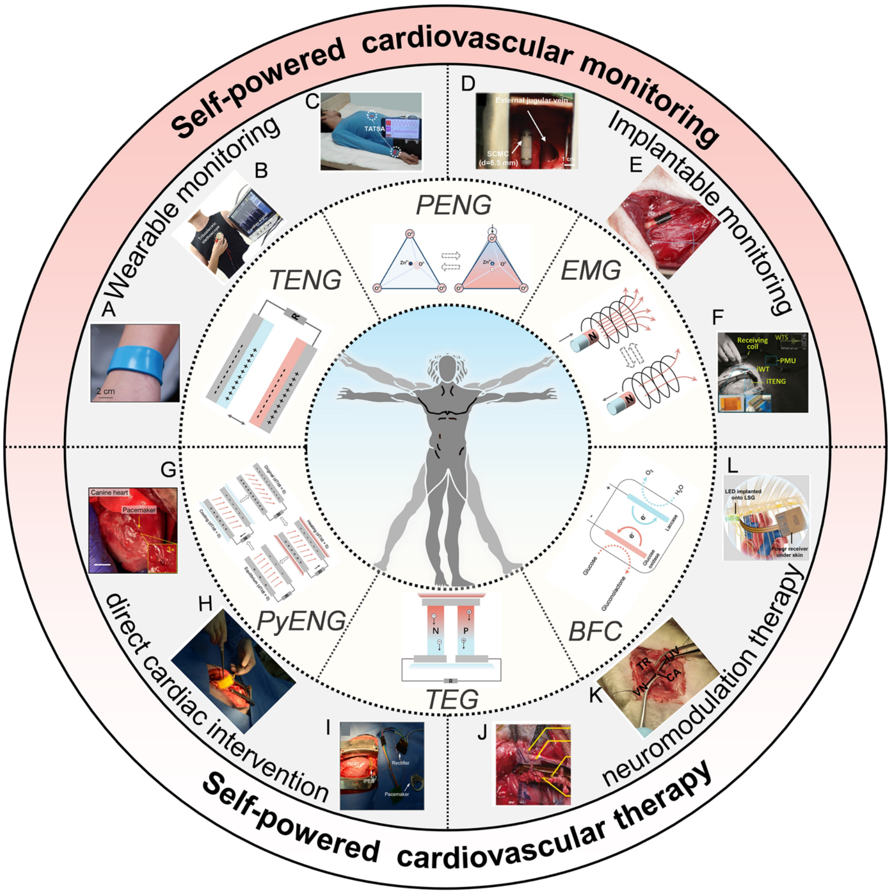

Figure 1. Schematic of self-powered technologies and self-powered cardiovascular medical devices. The figure includes 6 major types of self-powered generators: triboelectric nanogenerator (TENG), piezoelectric nanogenerator (PENG), electromagnetic generator (EMG), biofuel cell (BFC), thermoelectric generator (TEG), and pyroelectric nanogenerator (PyENG). (A) The wearable system for continuous wireless monitoring of arterial blood pressure. Reproduced with permission from Li et al.[34] Copyright 2023, Nature Publishing Group. (B) The triboelectric stethoscope. Reproduced with permission from Hui et al.[35] Copyright 2024, Wiley-VCH. (C) Washable sensor array fabric for precise monitoring of epidermal physiological signals. Reproduced with permission from Fan et al.[17] Copyright 2020, AAAS. (D) Bias-free cardiac monitoring capsule. Reproduced with permission from Qu et al.[4] Copyright 2024, Wiley-VCH. (E) Electronic vascular conduit for *in situ* identification of hemadostenosis and thrombosis. Reproduced with permission from Liu et al.[20] Copyright 2025, Nature Publishing Group. (F) TENG for real-time wireless heart monitoring. Reproduced with permission from Zheng et al.[36] Copyright 2016, American Chemical Society. (G) Millimeter-scale bioresorbable optoelectronic cardiac pacemaker. Reproduced with permission from Zhang et al.[8] Copyright 2025, Nature Publishing Group. (H) Symbiotic cardiac pacemaker. Reproduced with permission from Ouyang et al.[25] Copyright 2019, Nature Publishing Group. (I) Direct powering a real cardiac pacemaker by natural energy of a heartbeat. Reproduced with permission from Li et al.[37] Copyright 2019, American Chemical Society. (J) Flexible PENG for self-powered vagal neuromodulation. Reproduced with permission from Zhang et al.[38] Copyright 2021, Elsevier. (K) Closed-loop self-powered low-level vagus nerve stimulation system. Reproduced with permission from Sun et al.[30] Copyright 2022, Elsevier. (L) Wireless, self-powered optogenetic system for improving cardiac arrhythmias. Reproduced with permission from Zhou et al.[39] Copyright 2023, Wiley-VCH.

response, self-powered cardiovascular medical devices not only show great potential in improving the early diagnosis and treatment of CVDs but also provide a solid foundation for future personalized medicine and precision intervention.

In recent years, many review papers have been published on new cardiovascular medical electronic devices. For example, the article by Zheng et al.[2] introduces the latest progress in self-powered cardiovascular implantable electronic devices and wearable active sensors. In other reviews, some focus on soft bioelectronics in the equipment, emphasizing the flexibility and stretchability of the device[31]; some focus on the progress in the field of materials[32]; and some only focus on the application of TENG or PENG in this field.[33] Due to the rapid development of self-powered technologies, such as the invention of permanent magnet fluids, and the changing clinical needs, such as the need for wearable heart sound monitoring devices and the treatment of heart disease through neural regulation, it is necessary to update relevant reviews in a timely manner. This review has the latest introduction to new self-powered technologies, new cardiovascular monitoring devices, and new self-powered cardiovascular treatment strategies, and will provide researchers with newer and more comprehensive research ideas based on previous research.

This review focuses on self-powered cardiovascular medical devices, with the aim of showing how various self-powered technologies promote the innovation of traditional cardiovascular medical devices. As shown in Figure 1, we will first introduce the working mechanism and development status of various self-powered technologies in detail, and then systematically explain the current research progress and typical representative work of self-powered cardiovascular medical devices from the 2 major application fields of monitoring and treatment, and explore the challenges and development prospects faced by this field, to provide reference and inspiration for subsequent research and clinical transformation.

2. Self-powered technologies

2.1. Introduction to self-powered technologies

Self-powered technologies refer to systems that harvest and convert ambient or body-generated energy—such as mechanical, thermal, or biochemical energy—into electricity to drive sensing, data transmission, or therapeutic functions. Unlike conventional devices that rely on batteries or external power supplies, self-powered systems operate continuously and autonomously, making them particularly suitable for wearable and implantable medical devices that demand long-term operation, miniaturization, and biocompatibility. In the field of cardiovascular medicine, self-powered technologies offer a new approach for realizing real-time, long-term, and physiologically adaptive health monitoring and intervention. In recent years, the rapid advancement of biomedical engineering and flexible electronics has propelled the development of self-powered technologies—systems capable of harvesting ambient energy to sustain their operation without the need for traditional batteries. These technologies show great promise in cardiovascular medicine, where long-term, continuous monitoring and therapy are essential for managing chronic conditions such as hypertension, arrhythmia, and AF.

Self-powered systems are typically designed to convert various forms of energy naturally generated by the human body—including mechanical movements, thermal gradients, and biochemical reactions—into electrical energy. Compared with conventional battery-powered devices, self-powered medical devices offer several unique advantages: (1) sustainability, by utilizing inexhaustible physiological energy sources such as heartbeats or arterial pulsation; (2) miniaturization, as the elimination of batteries reduces overall device size and weight; (3) biocompatibility and long-term safety, by avoiding potential chemical leakage from batteries; and (4) integration with closed-loop systems, enabling real-time sensing and active intervention in a compact form. These characteristics are particularly beneficial in cardiovascular applications, where continuous and reliable physiological monitoring is essential. Self-powered technologies make it feasible to design implantable or wearable devices that track dynamic cardiovascular parameters—such as pulse waveform, BP, and heart rhythm—over extended periods. Moreover, beyond monitoring, some self-powered devices are also capable of therapeutic functions, such as electrical stimulation for rhythm regulation or localized drug delivery powered by harvested energy.

Driven by innovations in materials science, nanotechnology, and microfabrication, researchers have developed various energy harvesting mechanisms suitable for different energy sources. Among them, TENGs and PENGs have garnered significant attention for their high sensitivity to mechanical deformation and compatibility with soft tissue interfaces. Other techniques such as thermoelectric generators (TEGs), pyroelectric nanogenerators (PyENGs), electromagnetic generators (EMGs), and biofuel cells (BFCs) are also being explored, although each type has distinct strengths and limitations depending on the application scenario.

2.2. Working principles of self-powered technologies

Self-powered technologies convert ambient energy sources into electricity, eliminating the need for conventional batteries. These mechanisms are particularly valuable for wearable and implantable cardiovascular devices that require long-term, uninterrupted operation. This chapter details the working principles of various self-powered technologies.

2.2.1. Triboelectric nanogenerators. When 2 dissimilar materials come into contact and are then separated, an imbalance in electron affinity results in a net transfer of electrons, leading to surface charge accumulation. This principle underlies TENGs, where periodic mechanical motions induce alternating current signals.[40–43] As shown in Figure 2A, 4 fundamental operation modes have been established: vertical contact–separation, single-electrode mode, lateral sliding, and freestanding mode. These configurations allow TENGs to respond flexibly to various biomechanical inputs, such as skin stretching, arterial pulse, or chest movement, by maximizing interfacial charge generation and transfer. To understand the origin of the triboelectric effect, electron behavior at the microscopic level can be described using the concept of electron-cloud potential wells. When 2 surfaces are brought into close proximity, their electron clouds interact, and energy is redistributed based on the depth of these potential wells. Upon separation, this redistribution results in a charge imbalance, which drives electron flow through an external circuit. Concurrently, the mechanism of charge transfer is often described using energy band diagrams, which reveal how differing Fermi levels and surface states dictate the direction and magnitude of electron migration.[43–45]

2.2.2. Electromagnetic generators. It is well known that the basic principle of an EMG is to convert kinetic energy into electrical energy using the law of electromagnetic induction. Since the invention of the first alternator in 1866,

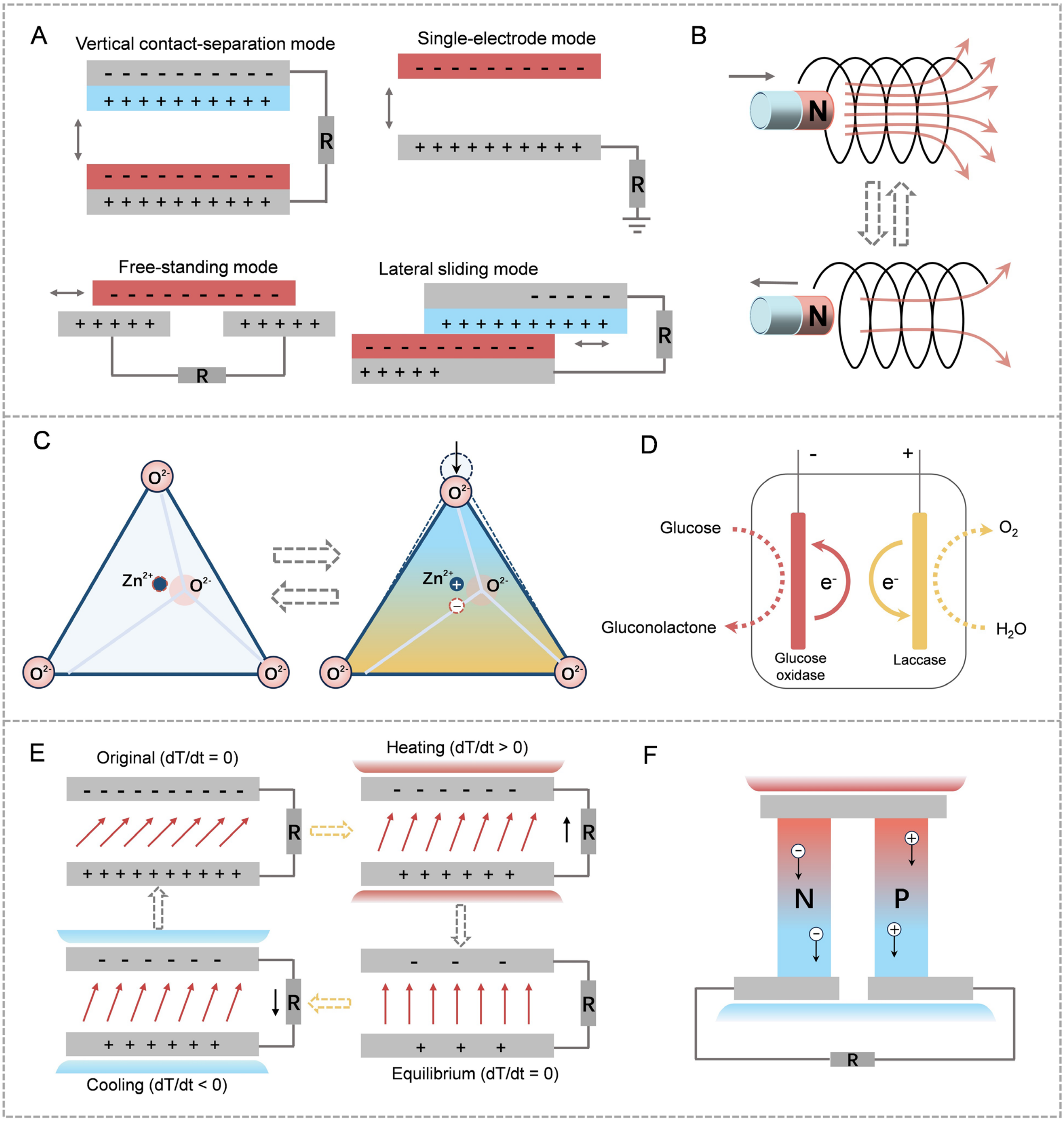

Figure 2. Working principles of self-powered technologies. (A) Structural design of triboelectric nanogenerators. (B) Law of electromagnetic induction. (C) Piezoelectric effect. (D) A typical biofuel cell uses enzymes as catalysts for glucose oxidation at the anode and oxygen reduction at the cathode. (E) Working principle of pyroelectric generators. (F) Working principle of thermoelectric generators.

the EMG has become a great driving force for the progress of human society and a core pillar of modern energy. EMGs are generally composed of stator, rotor, end caps, bearings, and other components. Driven by external forces, the rotor rotates in the stator, making the movement of cutting the magnetic inductance, due to the law of electromagnetic induction, to generate induced electric potential, thus generating current in the external circuit (Fig. 2B).[46]

2.2.3. Piezoelectric nanogenerators. PENGs, by contrast, rely on the intrinsic asymmetry of certain crystal structures. When subjected to mechanical deformation, such materials develop an electric potential due to realignment of dipole moments. This is known as the direct piezoelectric effect, and is visualized in Figure 2C, where external tensile force induces a charge separation across the material. This allows energy to be harvested from periodic physiological activities such as heartbeats or respiratory motions.[47–50] Conversely, when an electric field is applied across the same material, mechanical strain is generated—this converse piezoelectric effect can be utilized in closed-loop therapeutic stimulation devices, providing both energy harvesting and actuation capability in a single system.

2.2.4. Biofuel cells. BFC is an important and promising self-powered power generation technology. Its working principle is to directly obtain biochemical energy from biological fluids (such as blood, body fluids, or tissue fluids) and convert it into electrical energy. As shown in Figure 2D, this is the working principle of a typical enzyme-catalyzed BFCs. At the anode, glucose dehydrogenase (or other oxidases) acts as a biocatalyst to catalyze the oxidation reaction of glucose molecules, releasing electrons and protons; electrons are transmitted to the cathode through an external circuit to drive current output; at the cathode, the reduction reaction of molecular oxygen is usually catalyzed by peroxidase or dopamine oxidase, thereby completing the entire current closed loop. Since the reaction substrates (such as glucose and oxygen) are widely present in the body environment, BFCs have the advantages for long-term stable operation and high compatibility with the biological environment.[51,52]

2.2.5. Pyroelectric nanogenerators. PyENGs are energy harvesting devices that utilize nanomaterials with the pyroelectric effect to convert thermal energy into electrical energy. The pyroelectric effect refers to the change of spontaneous polarization of certain crystals when they are heated to different temperatures. The working principle of PyENGs is that when the temperature is certain, the crystals have a stable strength of spontaneous polarization; when the temperature increases or decreases, it will lead to a decrease or increase of the strength of spontaneous polarization, which induces a change of charge on the electrodes, and causes the generation of a pyroelectric current in the circuit (Fig. 2E).[53]

2.2.6. Thermoelectric generators. TEGs harness temperature gradients to produce electricity through the Seebeck effect, where charge carriers in semiconductors move from a hot side to a cold side, generating voltage. Figure 2F demonstrates this concept, highlighting the movement of electrons and holes within p-type and n-type materials. In biomedical settings, TEGs can exploit the heat differential between human skin and ambient air to power low-energy sensors.[54–57] The inverse process, the Peltier effect, can cause localized heating or cooling when current is passed through the same structure.[58,59] While the Peltier effect is more commonly applied in active thermal modulation, its coupling with Seebeck-based generators opens possibilities for dual-mode medical devices that combine sensing with therapy.[60–62]

In general, TENGs, PENGs, and EMGs all convert mechanical energy into electrical energy. Among them, the output characteristics of TENGs are high voltage and low current, the output of PENGs is low voltage and low current, and the output of EMG is high current and low voltage. The 3 have similar application scenarios and complementary advantages. Whether they are used alone or as composite devices, they all play an important role in the field of self-powered cardiovascular medical devices. BFCs convert chemical energy into electrical energy. They have a simple structure, can be miniaturized, and are highly coupled to the physiological environment. PyENG and TEG both have the ability to convert thermal energy into electrical energy, but the difference is that the former uses thermal energy that changes with time, while the latter uses thermal energy that changes with space. Moreover, PyENG has a large output voltage and a small current. Its output depends on the rate of temperature change. It can be used to monitor changes in human body temperature and fluctuations in internal organ temperature. TEG has a large current and a relatively high-power density. It is easy to output in series, but requires a stable heat source and heat dissipation conditions. It can be used to collect human body temperature and realize self-powering of wearable devices. The above energy harvesting technologies have their own characteristics and application scenarios. For self-powered cardiovascular medical devices, their application still faces many challenges that need to be solved urgently, such as low-power density, poor tissue mechanical matching, and long-term instability. In subsequent research, it is necessary to reasonably select energy harvesting technology based on factors such as the monitored object, usage environment, and performance pursuit. Collectively, these energy conversion principles lay the foundation for the development of self-powered cardiovascular medical systems. In the following section, we will examine representative device designs that incorporate these mechanisms, demonstrating their translational potential in real-world diagnostic and therapeutic applications.

3. Self-powered cardiovascular monitoring

CVDs are characterized by high mortality, high disability and sudden onset, and effective early monitoring and intervention will greatly improve the survival rate of patients.[33,63] Currently, clinical monitoring of BP, ECG, heart sounds, and oxygen saturation is the standard approach for early diagnosis and management. However, the bulky nature of traditional clinical equipment limits its suitability for long-term, portable use. The rapid advancement of self-powered technologies is accelerating the development of battery-free, long-term cardiovascular monitoring solutions. This chapter presents a comprehensive overview of recent progress in cardiovascular monitoring devices, focusing on both wearable and implantable systems. These innovations have the potential to revolutionize clinical monitoring practices and pave the way for personalized medicine.

3.1. Wearable self-powered cardiovascular monitoring devices

In recent decades, advancements in the field of flexible electronics have significantly accelerated the development of wearable medical devices, enabling noninvasive and nonintrusive diagnosis and prevention of CVDs. Flexible

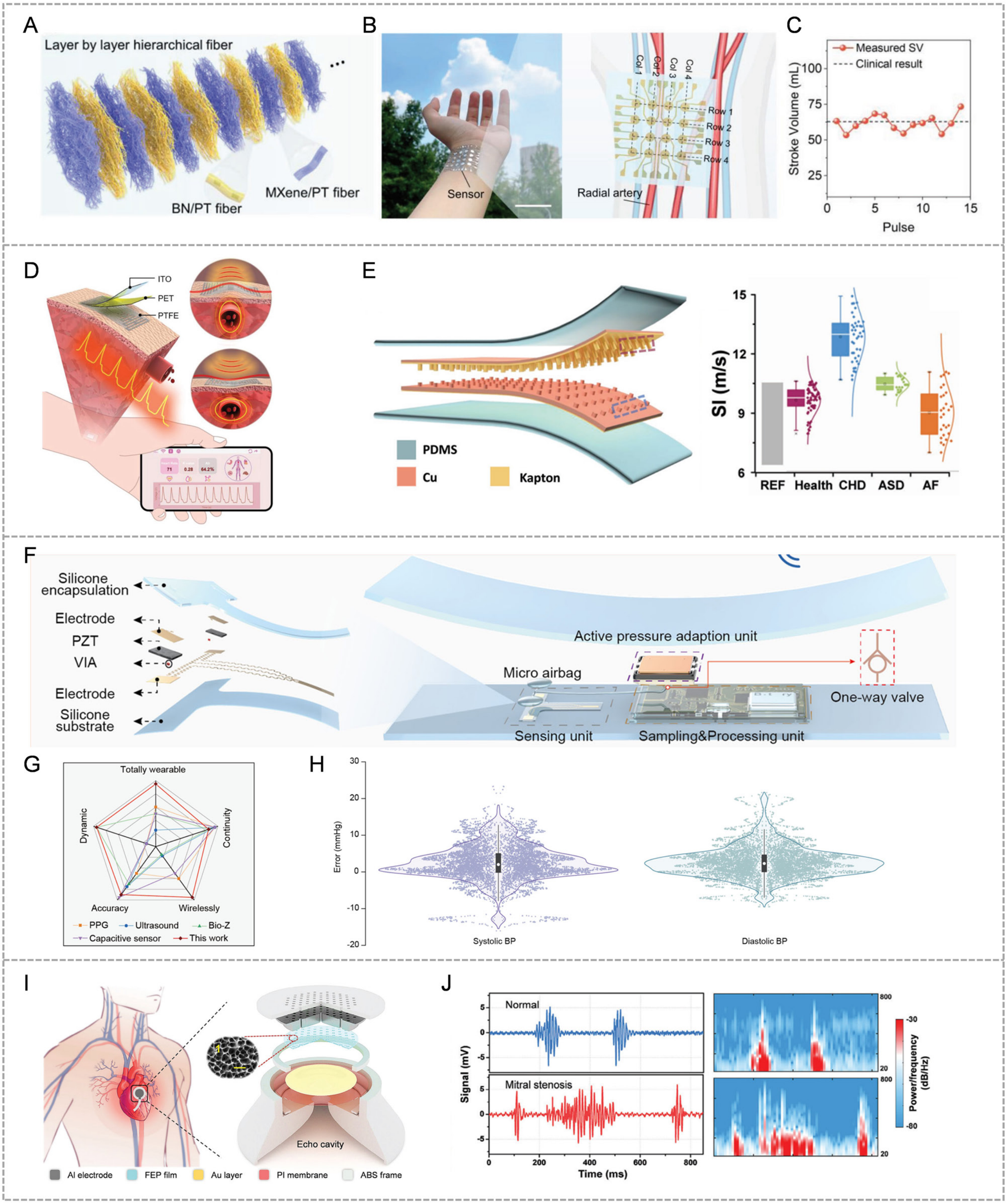

Figure 3. Mechanism-driven wearable self-powered cardiovascular monitoring devices. (A) A wearable blood pressure sensor based on a heterogeneously hierarchical piezoelectric composite. (B) and (C) The sensor array and their test results compared to clinical means. Reproduced with permission from Tian et al.[14] Copyright 2024, Wiley-VCH. (D) A conformal pressure sensor inspired by kirigami structure. Reproduced with permission from Meng et al.[15] Copyright 2022, Wiley-VCH. (E) Pulse sensors with excellent detection of cardiovascular diseases such as coronary artery disease, atrial septal defects, and atrial fibrillation. Reproduced with permission from Ouyang et al.[64] Copyright 2017, Wiley-VCH. (F–H) A wearable system capable of continuous blood pressure monitoring that integrates a piezoelectric sensor array, an active pressure adaptation unit, a signal processing module, and advanced machine learning algorithms. Reproduced with permission from Li et al.[34] Copyright 2023, Nature Publishing Group. (I) and (J) The power-law-shaped auscultatory cavity. Reproduced with permission from Hui et al.[35] Copyright 2024, Wiley-VCH.

piezoelectric composites offer a new option for noninvasive and continuous BP monitoring. As shown in Figure 3A, Tian et al.[14] reported a wearable BP sensor based on a heterogeneously hierarchical piezoelectric composite with a remarkable piezoelectric charge coefficient of 41.67 $pC \cdot N^{-1}$. The designed sensor array is capable of measuring local pulse wave velocity and calculating relevant cardiovascular parameters (Fig. 3B). The results show good agreement with those obtained from clinical Doppler ultrasound methods, providing meaningful reference data for clinical diagnosis (Fig. 3C). To address the issue of motion artifacts commonly affecting wearable pulse sensors, Meng et al.[15] developed a highly sensitive and conformal pressure sensor inspired by kirigami structure. This device showed a superior sensitivity (35.2 $mV \cdot Pa^{-1}$) and remarkable stability (> 84,000 cycles) (Fig. 3D). Similarly, the pulse sensor developed by Ouyang et al.[64] demonstrates excellent detection capability for cardiovascular conditions such as coronary heart disease, atrial septal defect, and AF (Fig. 3E).

The aforementioned studies have primarily focused on sensor unit design and material innovation while overlooking the complexity of backend signal acquisition and data processing. As shown in Figure 3F, a thin, soft, miniaturized system (TSMS) capable of continuous BP monitoring has been developed (TSMS), integrating a piezoelectric sensor array, an active pressure adaptation unit, a signal processing module, and advanced machine learning algorithms, all within a truly wearable form factor.[34] TSMS represents a state-of-the-art solution for continuous BP monitoring, excelling in wearability, accuracy, continuity, dynamic responsiveness, and various other key performance aspects (Fig. 3G). The measurement accuracy of the TSMS system was validated in a study involving 87 volunteers using a commercially available continuous noninvasive arterial pressure monitoring device. As shown in Figure 3H, the TSMS achieved over 98% accuracy in both systolic and diastolic pressure measurements, with errors < 15 mmHg.

In addition to pulse and BP signals, low-intensity, low-frequency heart sounds also provide important clinical information for the identification and diagnosis of various cardiac diseases. Leveraging the fast saturated constitutive characteristic and the relatively independent mechanoperception and electromechanical conversion component of TENG, a power-law-shaped auscultatory cavity was developed to improve the acoustic impedance matching and acoustic energy converging, achieving a signal-to-noise ratio as high as 36 dB (Fig. 3I).[35] With the integration of machine learning, this stethoscope is capable of diagnosing 5 different cardiac conditions with an accuracy of 97% (Fig. 3J), offering a new direction for the development of advanced intelligent medical devices.

The sensing technologies embedded in these wearables span a wide range of modalities, each tailored to specific diagnostic needs. Photoplethysmography (PPG) sensors, commonly integrated into smartwatches and patches, provide continuous pulse wave analysis for heart rate monitoring, oxygen saturation assessment, and even early detection of vascular stiffness. Meanwhile, single-lead or multilead ECG systems enable precise arrhythmia detection, with some advanced devices incorporating AI algorithms to differentiate between benign and pathological rhythms. Emerging hybrid designs combine PPG, ECG, and even seismocardiography to derive additional metrics such as pulse arrival time for cuffless BP estimation, offering a more holistic view of cardiovascular health. From a clinical perspective, these devices are proving invaluable in both preventive and diagnostic medicine. They facilitate early detection of AF, a leading cause of stroke, by capturing irregular rhythms that might otherwise go unnoticed during sporadic clinical visits. Additionally, continuous BP monitoring via pulse wave analysis allows for better management of hypertension, while vascular reactivity assessments—such as the reactive hyperemia index—provide insights into endothelial dysfunction, a precursor to atherosclerosis. Beyond diagnostics, these wearables are increasingly used in postoperative care and chronic disease management, where real-time data can alert patients and physicians to deteriorating conditions before complications arise.

Shown in Figure 4A, Si et al.[41] developed a highly sensitive triboelectric sensor with a 3D interlocked all-textile structure, featuring excellent breathability and water resistance. It can continuously and accurately monitor epidermal pulse waves under sweat, immersion, and shallow water conditions, enhancing the practicality of e-textiles for all-weather health monitoring and early CVD diagnosis. As illustrated in Figure 4B, Wang et al.[65] designed and fabricated a double-layer TENG composed of biocompatible expanded polytetrafluoroethylene and poly(3-hydroxybutyrate) membranes for self-powered, real-time hemodynamic monitoring of vascular grafts. The device exhibited stable energy harvesting and storage capabilities while supporting human umbilical vein endothelial cell growth, demonstrating its potential as a smart vascular graft for early detection of thrombosis and stenosis. As illustrated in Figure 4C, this study developed a wireless self-powered optogenetic modulation system based on a TENG that harvests energy from body motion to enable long-term, precise cardiac neuromodulation.[39] The system effectively suppressed postmyocardial infarction (MI) sympathetic remodeling and hyperactivity in ambulatory canines, significantly improving ventricular function, reducing infarct size, enhancing electrophysiological stability, and decreasing susceptibility to malignant arrhythmias. This wireless optogenetic modulation technology shows promising translational potential for treating arrhythmias and CVDs related to sympathetic hyperactivity, and offers new opportunities for implantable or wearable self-controlled long-term optogenetic therapy devices. As shown in Figure 4D, Wang et al.[66] developed a dual-modal wearable pulse detection system integrating a PENG and a PPG sensor with a biomimetic fingertip structure for high-accuracy and low-power

Figure 4. Application-oriented and intelligent wearable self-powered cardiovascular systems. (A) 3D interlocked all-textile structured triboelectric epidermal pulse waves pressure sensor. Reproduced with permission from Si et al.[41] Copyright 2024, Springer. (B) TENG sensing vascular grafts. Reproduced with permission from Wang et al.[65] Copyright 2023, Elsevier. (C) Wireless self-powered optogenetic system. Reproduced with permission from Zhou et al.[39] Copyright 2023, Wiley-VCH. (D) Dual-modal wearable sleep apnea sensor. Reproduced with permission from Wang et al.[66] Copyright 2025, Wiley-VCH. (E) Personalized blood pressure sensor. Reproduced with permission from Yao et al.[67] Copyright 2023, American Chemical Society. (F) Deep learning cardiovascular classifier. Reproduced with permission from Sun et al.[68] Copyright 2024, Elsevier. (G) Stretchable triboelectric sensor. Reproduced with permission from Yang et al.[69] Copyright 2025, Elsevier. (H) Flexible piezoresistive blood pressure monitoring system. Reproduced with permission from Zhang et al.[70] Copyright 2025, Springer.

monitoring of sleep apnea syndrome. Given that polysomnography, the clinical gold standard, was limited by its cost, complexity, and interference with sleep quality, the proposed system adopted a two-stage detection strategy. The self-powered PENG performed continuous preliminary screening and activated the PPG sensor only when suspicious events were detected. A vision transformer-based deep learning model was employed to enhance detection performance. The high-accuracy single-modal configuration achieved 99.59% accuracy, while the low-power dual-modal approach maintained 94.95% accuracy. This wearable system effectively overcame the limitations of traditional polysomnography, offering high diagnostic performance with significantly lower power consumption. Its practicality in both home and clinical settings offered great promise for improving early diagnosis and treatment outcomes for sleep apnea syndrome patients.

As shown in Figure 4E, Yao et al.[67] constructed a flexible triboelectric pulse sensor based on a biomimetic nanopillar structure and integrated it with personalized machine learning for cuffless, continuous BP monitoring. Conductive nanopillars were fabricated by soft lithographic replication of a cicada wing, effectively enhancing output performance to detect weak pulse signals. The sensor was coupled with an individualized partial least-squares regression model to accurately derive unknown BP values, overcoming the limitations of general models when facing interpatient variability. This intelligent and noninvasive system demonstrated excellent sensitivity and accuracy, suggesting strong potential as a long-term wearable platform for hypertension management and cardiovascular care. As shown in Figure 4F, Sun et al.[68] developed an intelligent CVD diagnosis system combining a 2D Bi_2O_2Se-based PENG with deep learning. The wearable self-powered PENG captures key pulse waveform features for accurate identification of 9 common CVDs, achieving 93.75% accuracy in clinical trials. This work highlights the great potential of 2D PENGs in long-term, noninvasive health monitoring. As shown in Figure 4G, Yang et al.[69] proposed and fabricated a stretchable silicone rubber-based triboelectric sensor to address the limitations of conventional single-electrode stretchable sensors, including poor stability, complex structure, and limited force detection range. The sensor demonstrated excellent flexibility and comfort, with the capability to detect forces ranging from as low as 0.002 N to as high as 300 N. It maintained performance stability over 12,000 loading cycles. In practical applications, the silicone rubber-based triboelectric-sensor successfully monitored human pulse waves, throat movements, and limb activities. Integrated with embedded systems, wireless transmission, and neural network algorithms, the system enabled human–computer interaction, activity recognition, and remote fall detection, indicating strong potential for intelligent elderly care. Figure 4H shows a flexible piezoresistive sensor based on polydopamine and carbon nanotubes developed by Zhang et al.[70] for cuffless BP monitoring via pulse wave velocity. The sensor features high sensitivity (6.23 kPa^{-1}), wide linear range (0–350 kPa), low detection limit (< 100 Pa), and fast response time (100 ms), maintaining stable performance after 10,000 compression cycles. A multiparameter BP estimation model was established, outperforming simple models, with results consistent with commercial sphygmomanometers. This research provides a simple, low-cost solution for long-term cardiovascular monitoring, but issues such as motion artifacts, energy efficiency limitations, and strict clinical validation requirements still pose ongoing challenges.

Wearable self-powered cardiovascular monitoring devices have significantly promoted continuous, noninvasive, and personalized cardiovascular health management, and facilitated early diagnosis and intervention. In recent years, the introduction of artificial intelligence algorithms has improved the accuracy of data processing and anomaly detection, and multimodal fusion and wireless transmission have enhanced the integration and practicality of equipment. However, this field still faces challenges such as insufficient energy supply efficiency, motion artifact interference, and insufficient long-term stability verification. In the future, we should focus on improving energy efficiency and signal stability, optimizing AI-driven data analysis capabilities, promoting device integration and flexible design, and accelerating standardized verification and clinical transformation to promote its application in real scenarios.

3.2. Implantable self-powered cardiovascular monitoring devices

Although wearable sensors offer significant advantages in terms of convenience and minimal invasiveness, their accuracy and resolution are limited by their distance from the heart. This makes them more susceptible to motion artifacts and noise generated by other intrathoracic structures, such as the lungs and skeletal muscles. In contrast, implantable sensors, which are directly connected to the heart or arterial vessels, enable more precise monitoring of cardiovascular parameters.[32]

For patients with early-stage impairment of cardiac contractility, invasive implantable monitoring devices offer more accurate cardiac functional parameters compared to wearable devices. Continuous monitoring of abnormal changes in myocardial contractility can facilitate the early detection of potential CVDs. Based on this, Qu et al. developed a bias-free cardiac monitoring capsule (BCMC), which can be implanted into the heart chamber of animal models through minimally invasive intervention (Fig. 5A).[4] The device is driven by the heart's natural systolic and diastolic motions, enabling its internal rolling TENG to generate electrical signals that directly reflect myocardial contractility (Fig. 5B). This allows for real-time, accurate, and comprehensive monitoring of cardiac function in patients with AF. As shown in Figure 5C, the BCMC is capable of detecting nonsustained ventricular tachyarrhythmia in vivo, clearly capturing fluctuations in myocardial contractility and changes in heart rate during nonsustained ventricular tachyarrhythmia episodes. Monitoring vascular health is of great importance for postoperative recovery in patients with coronary artery disease or peripheral artery disease, as it helps prevent intimal hyperplasia and thrombosis. Liu et al.[20] proposed an electronic blood vessel by integrating flexible sensors into a biomimetic vascular graft (Fig. 5D). This system enabled wireless, *in situ* monitoring of restenosis and thrombosis after surgical implantation in male nonhuman primates (cynomolgus monkeys). Similarly, Figure 5E shows a directly 3D-printed artificial artery with an embedded piezoelectric sensor, offering

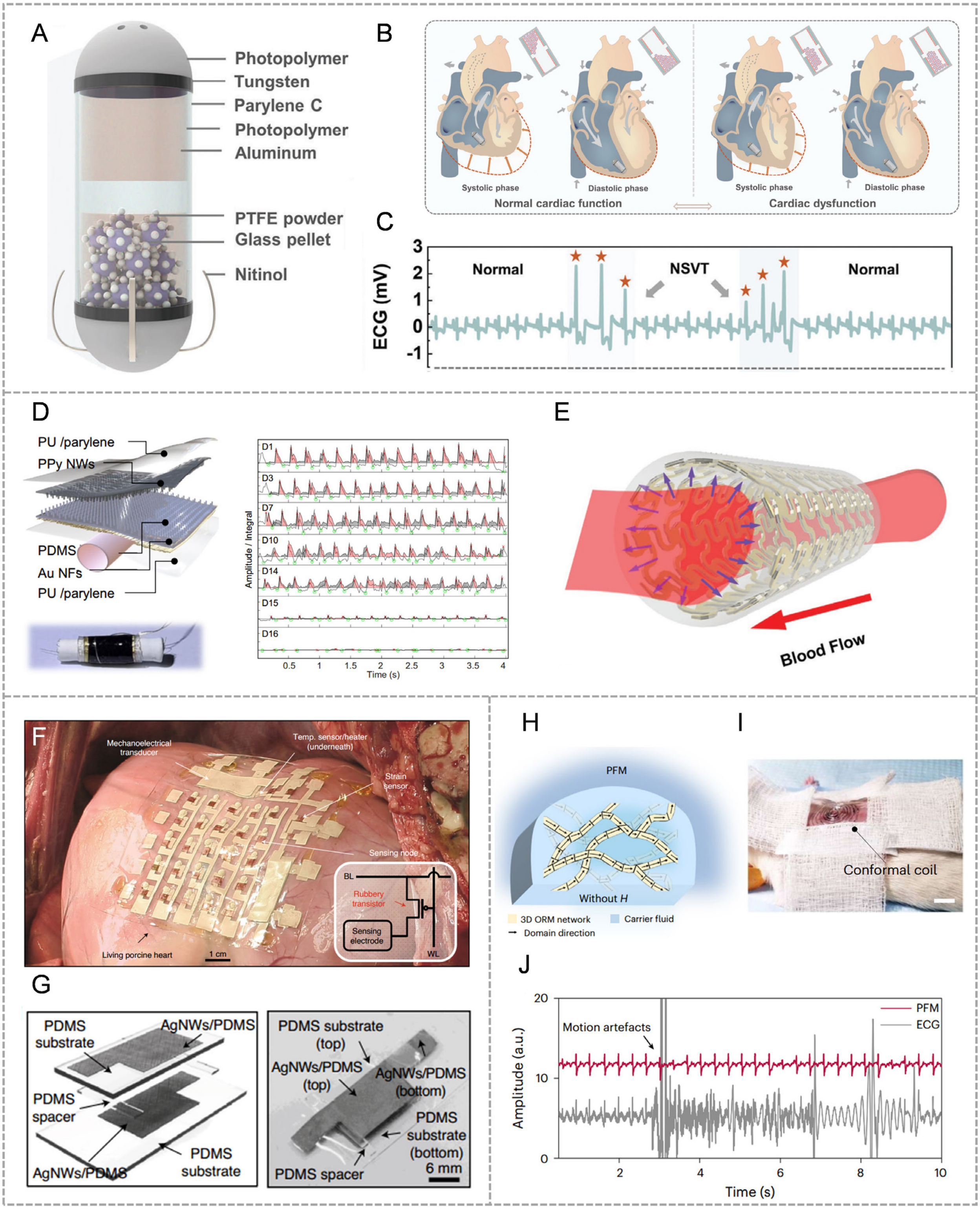

Figure 5. Implantable self-powered cardiovascular monitoring devices. (A–C) A bias-free cardiac monitoring capsule. Reproduced with permission from Qu et al.[4] Copyright 2024, Wiley-VCH. (D) An electronic blood vessel by integrating flexible sensors into a biomimetic vascular graft for postoperative vascular graft monitoring. Reproduced with permission from Liu et al.[20] Copyright 2025, Nature Publishing Group. (E) The directly 3D-printed artificial artery with an embedded piezoelectric sensor. Reproduced with permission from Li et al.[71] Copyright 2020, Wiley-VCH. (F) A fully soft rubber-based epicardial patch and (G) triboelectric nanogenerator module harvests energy from heartbeats to power patches. Reproduced with permission from Sim et al.[5] Copyright 2020, Nature Publishing Group. (H) Permanent fluidic magnets. (I) Injectable and recyclable permanent fluid magnet-based liquid bioelectronics for heartbeat monitoring in rats. (J) The electrical signals produced by the PFM are more robust than those from ECG. Reproduced with permission from Zhao et al.[10] Copyright 2024, Nature Publishing Group.

a sensitivity of 0.306 mV·mmHg^{-1}, capable of detecting early-stage vascular occlusion.[71] Epicardial bioelectronic patches are important tools for studying and treating heart diseases. As shown in Figure 5F, a fully soft rubber-based epicardial patch was developed with a modulus comparable to that of cardiac tissue, enabling the monitoring of electrophysiological activity, strain, and temperature.[5] A TENG is integrated into the patch to harvest energy from heartbeats, providing an additional power source for the device (Fig. 5G).

Although ultrathin-membrane-based bioelectronic devices can conform to biological tissues, mechanical mismatches between solid materials and biological tissues still exist.[72,73] In 2024, Zhao et al. developed a permanent fluid magnet (PFM) that offers a promising solution to this issue.[10] They used non-Brownian magnetic particles to create a three-dimensional oriented and ramified magnetic network structure in a carrier fluid to decouple the particle Brownian motion and colloidal stability (Fig. 5H). The PFM exhibits high coercivity (~699.91 Oe), flowability, stability, and decent reconfigurability. Through open-chest surgery, PFM was injected onto the surface of the rat pericardium using a syringe, and a 20-mm conformal coil was attached to the skin (Fig. 5I). The mechanical motion of the heart was monitored by detecting induced current signals generated via electromagnetic induction. As shown in Figure 5J, the electrical signals produced by the PFM were more robust than those from ECG, demonstrating better resistance to mechanical interference. The development of PFM marks the beginning of a new direction in liquid bioelectronics research.

Implantable cardiovascular monitoring devices have higher accuracy and resolution than wearable devices, and can achieve direct and continuous monitoring of cardiac and vascular parameters. Recently developed devices such as BCMC and 3D-printed artificial arteries have shown good prospects in real-time and accurate monitoring of myocardial contractility, vascular health, and electrophysiological activity. In addition, the development of liquid bioelectronics such as PFM systems has provided new ideas for solving the problems of mechanical mismatch between solid devices and biological tissues and signal stability. However, such implantable systems still face challenges in long-term biocompatibility, mechanical matching with soft tissues, wireless data transmission, and stable energy supply in the body. In the future, we should focus on promoting device miniaturization, wireless communication integration, self-powered operation, large animal, and clinical verification, and accelerating the development of continuous, accurate, and patient-friendly cardiovascular monitoring devices.

4. Self-powered cardiovascular therapy

Wearable and implantable cardiovascular monitoring devices can achieve continuous, dynamic, and high-precision monitoring of early CVD, which helps to timely identify the disease and assess the risk, thereby significantly improving the timeliness and accuracy of CVD management. The multiparameter physiological information obtained by these devices provides a more comprehensive diagnostic basis for clinicians. However, effective diagnosis is only the first step in disease management. As the condition progresses, especially after a clear diagnosis, clinical treatment becomes crucial for controlling the disease, improving prognosis, and enhancing quality of life. Current clinical approaches include cardiac pacemaker implantation, radiofrequency ablation, pharmacotherapy, and surgical procedures such as valve replacement or transplantation, which are widely used to treat arrhythmia, AF, and aortic valve stenosis. This chapter provides a comprehensive overview of the rapid advancements in cardiovascular therapeutic devices from 2 perspectives: direct cardiac intervention and neuromodulation therapy. The focus is on emerging technologies and applications, including self-powered cardiac pacemakers, cardiac patches, and VNS.

4.1. Self-powered direct cardiac intervention therapy

As a representative approach in bioelectronic therapy, the cardiac pacemaker is a key tool for managing arrhythmias. Temporary pacemakers are primarily used for short-term monitoring and intervention following cardiac surgery, making them suitable for the treatment of transient bradycardia. In contrast, permanent pacemakers are widely applied in patients with chronic bradycardia or conduction block, providing continuous and stable maintenance of normal heart rhythm. Conventional temporary pacemakers require lead placement on the epicardium or through the venous system. However, intravascular procedures pose significant challenges for adult patients with contraindications to transvenous pacing, as well as for pediatric patients with small body size and rapid growth. Repeat surgeries can complicate postoperative recovery and increase the risk of infection. To address these limitations, the team led by John A. Rogers developed a millimeter-scale, bioresorbable, and optoelectronic temporary cardiac pacemaker (Fig. 6A).[8] This device directly uses the battery electrodes as pacing leads, making it more than 23 times smaller than any existing bioresorbable alternative. It can be implanted through minimally invasive surgical procedures such as percutaneous injection or intravascular delivery, and has successfully achieved cardiac pacing at 240 bpm in canine models (Fig. 6B). Even more exciting is that this millimeter-scale temporary cardiac pacemaker enables time-synchronized, multisite pacing through programmable optoelectronic control (Fig. 6C). It can also be integrated into prosthetic heart valves for use in temporary pacing following transcatheter aortic valve replacement, addressing the commonly occurring atrioventricular conduction block after the procedure (Fig. 6D). As for permanent pacemakers, traditional devices are associated with complications such as pocket hematoma, lead-related infections, and skin scarring. The advent of leadless pacemakers has effectively addressed these issues. However, leadless pacemakers face challenges in long-term use, including limited

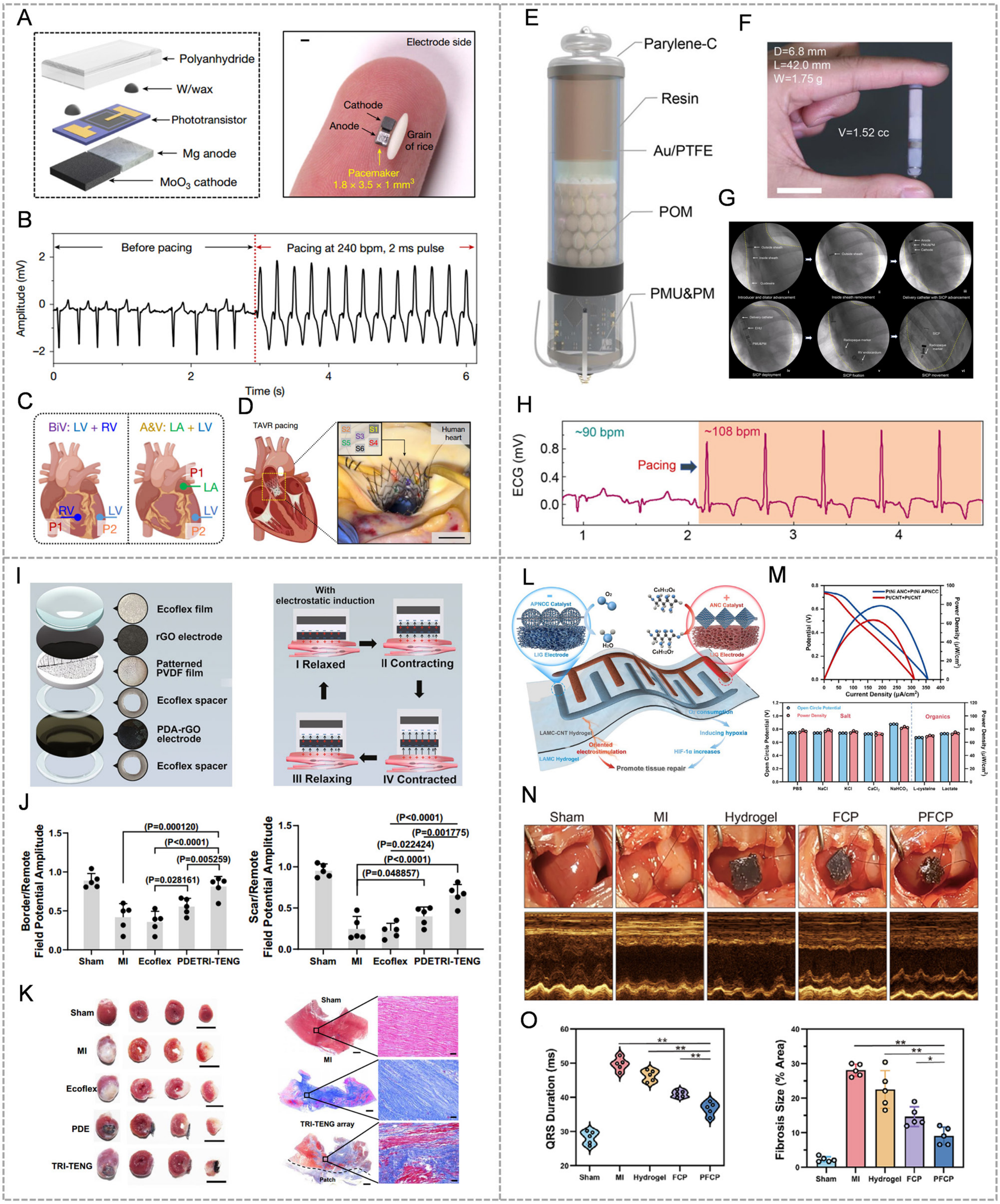

Figure 6. Direct cardiac interventions self-powered cardiovascular therapy. (A) Millimeter-scale bioresorbable optoelectronic cardiac pacemaker. (B) Heart rate can be paced to 240 bpm in canine models. (C) Time-synchronized, multisite pacing. (D) Integration with TVAR for postoperative temporary pacing. Reproduced with permission from Zhang et al.[8] Copyright 2025, Nature Publishing Group. (E) and (F) Capsule type self-powered leadless pacemaker. (G) and (H) The device was delivered to the right ventricle of the porcine model via catheter and successfully achieved long-term *in vivo* pacing. Reproduced with permission from Liu et al.[74] Copyright 2024, Nature Publishing Group. (I) A miniature self-powered biomimetic trinity TENG-based cardiac patch. (J) and (K) In both rat and porcine models, cardiac patches effectively repaired myocardial tissue and restored cardiac function. Reproduced with permission from Qiu et al.[24] Copyright 2024, Nature Publishing Group. (L) A fuel cell patch and (M) the output performance. (N) and (O) Myocardial tissue was effectively regenerated after 4 weeks of treatment. Reproduced with permission from Lin et al.[9] Copyright 2025, Wiley-VCH.

battery lifespan and the difficulty of surgical replacement. The development of self-powered technologies offers a promising solution to these limitations. Liu et al.[74] proposed a self-powered, leadless intracardiac pacemaker based on a TENG, which harvests energy from cardiac motion for the treatment of arrhythmias (Fig. 6E). The capsule-shaped device weighs only 1.75 g and has a volume of 1.52 cm^3(Fig. 6F). The device was integrated with a delivery catheter for transvenous implantation into the right ventricle of a swine model (Fig. 6G). Over a three-week follow-up period, it maintained stable pacing function, effectively increasing the heart rate from 90 to 108 bpm (Fig. 6H).

When MI occurs, an electrical conduction "dead zone" develops in the infarcted myocardium, followed by electrophysiological and structural remodeling, which is a major cause of sudden cardiac death. In recent years, cardiac patches have played a significant role in restoring heart function in infarcted regions by reconstructing the electroactive microenvironment.[75–77] Qiu et al.[24] developed a miniature self-powered biomimetic trinity TENG-based cardiac patch (TRI-TENG) capable of harvesting biomechanical energy from heartbeats to stimulate cardiomyocytes, effectively enhancing the electrical activity in infarcted cardiac tissue (Fig. 6I). Experimental results demonstrated that the TRI-TENG improved local electrical activity in the infarcted heart and enhanced overall electrical impulse propagation (Fig. 6J). In MI models of both rats and pigs, the TRI-TENG exhibited marked enhancement of cardiac function, surpassing the therapeutic efficacy of most conventional interventions (Fig. 6K). In addition to TENG-based cardiac patches, Lin et al.[9] reported a fuel cell patch (FCP) capable of providing *in situ* electrical stimulation and a hypoxic microenvironment to synergistically promote tissue repair (Fig. 6L). The flexible FCP conforms to tissues with varying morphologies, adheres firmly to prevent bacterial attachment, and delivers robust electrical stimulation (0.403 V, 51.55 $\mu W \cdot cm^{-2}$) (Fig. 6M). A flower-shaped FCP was fabricated, whose potential distribution aligned with the endogenous electric field in the injured myocardial region. After 4 weeks of treatment, most of the fibrotic tissue had reverted to normal, and the myocardium appeared red, indicating successful myocardial repair (Fig. 6N, O).

As an important means of direct cardiac intervention, self-powered pacemakers and cardiac patches have shown significant potential in the treatment of arrhythmias and cardiac repair after MI. Emerging devices such as millimeter-scale absorbable pacemakers, self-powered leadless pacemakers, TENG-based and fuel cell-based cardiac patches have achieved miniaturization, self-powered and multimodal electrical stimulation, providing solutions for long-term and stable maintenance of cardiac electrical activity. These devices make up for the shortcomings of existing pacemakers and other devices, such as limited life, bulky, and repeated surgery. However, they are still far from clinical conversion. In the future, energy collection efficiency and flexible packaging technology should be further optimized to promote large animal and clinical verification.

4.2. Self-powered neuromodulation therapy

In addition to the above-mentioned therapies based on direct cardiac intervention, in recent years, researchers have increasingly focused on treating CVDs by regulating the nervous system, which originated from the parallel research on the brain-heart axis.[27,78] Autonomic neuromodulation is a new treatment method that regulates the intrinsic cardiac nervous system by targeting specific components on the neural pathway, including the intrathoracic sympathetic ganglia, preganglionic axons of the vagus nerve, baroreceptors, and intrinsic cardiac ganglia. The neural pathways of the brain–heart axis include the sympathetic and parasympathetic branches of the autonomic nervous system (ANS). The vagus nerve is part of the parasympathetic nervous system and originates from the dorsal vagal nucleus and nucleus ambiguus in the medulla oblongata. After leaving the medulla, the vagus nerve travels along the preganglionic vagal efferent (descending) nerves to the carotid artery in the neck, where it branches into the left and right vagus nerves. These nerves pass through the chest to the cardiac plexus, innervating most of the visceral organs in the thoracic and abdominal cavities, including the heart, and play a vital role in regulating the electrical and mechanical functions of the heart (Fig. 7A).[79] Therefore, VNS stands out as a representative neuromodulation strategy, offering new therapeutic avenues for CVDs, with promising applications in AF, hypertension, and arrhythmias. Sun et al.[30] designed a closed-loop self-powered LL-VNS system for AF treatment. The LL-VNS main body is a hybrid nanogenerator, and the output performance of the device implanted in mice is consistent with the output required for AF treatment (Fig. 7B, C). According to statistical analysis, LL-VNS significantly shortened the duration of AF by 60% to 90% after treatment, effectively reduced myocardial damage, and effectively improved myocardial fibrosis and atrial junction protein levels. The effect was better when the stimulation intensity was 5 to 15 μA (Fig. 7D). The results showed that LL-VNS has an anti-inflammatory effect triggered by the NF-κB and AP-1 pathways in the mediating treatment system (Fig. 7E). Similarly, Zhang et al.[38] designed a PENG-based self-powered VNS device that could successfully harvest biomechanical energy from carotid artery pulsation to stimulate the vagus nerve (Fig. 7F). When the self-powered VNS device delivered electrical stimulation to the vagus nerve, the heart rate of the dog model decreased significantly (Fig. 7G).

In recent years, self-powered neuromodulation therapy has gradually attracted attention in the management of CVDs. Therapeutic strategies represented by VNS can precisely regulate cardiac electrical activity and BP by regulating the ANS, providing new treatment ideas for diseases such as AF, hypertension, and arrhythmias.

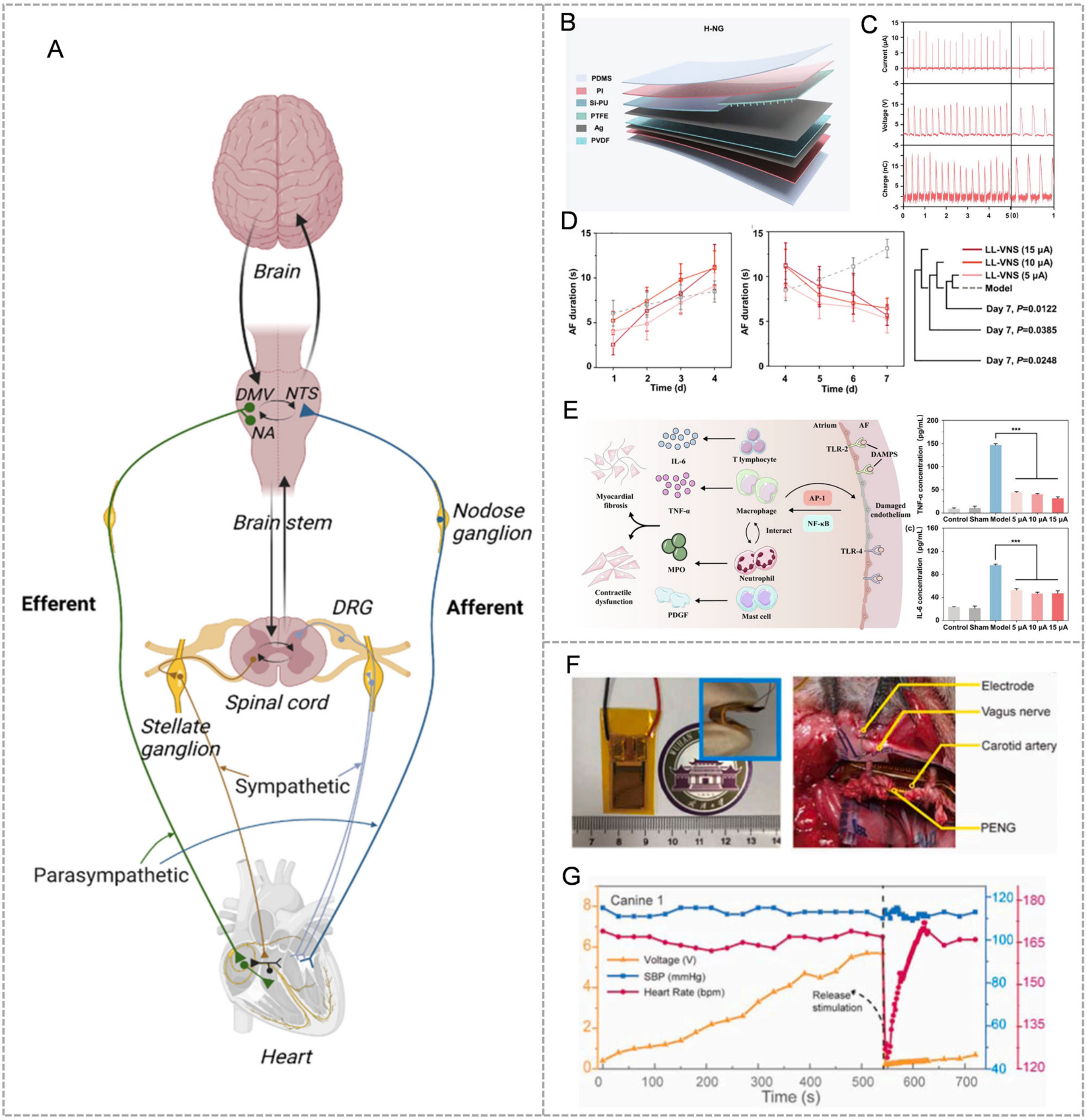

Figure 7. Neuromodulation self-powered cardiovascular therapy. (A) A schematic representation of neural control of the heart. Reproduced with permission from Zafeiropoulos et al.[79] Copyright 2023, Elsevier. (B) A closed-loop self-powered low-level vagus nerve stimulation system for AF treatment. (C) Output performance *in vivo*. (D) and (E) The therapeutic effect and signaling pathways of LL-VNS. Reproduced with permission from Sun et al.[30] Copyright 2022, Elsevier. (F) A PENG-based self-powered VNS device. (G) When LL-VNS was applied, the heart rate of the model dogs decreased significantly. Reproduced with permission from Zhang et al.[38] Copyright 2021, Elsevier.

Compared with direct cardiac intervention treatment strategies, neuromodulation therapy requires less energy and is less invasive. In the future, a closed-loop self-powered treatment system of "direct cardiac intervention + neuromodulation" can be constructed to achieve personalized and precise intervention for complex CVDs through the combination of local cardiac repair and ANS regulation.

Table 1 summarizes representative self-powered cardiovascular devices categorized into 2 major application domains: (A) monitoring devices and (B) therapy devices. Section A lists devices designed for real-time, *in situ* physiological signal acquisition and disease surveillance, such as heart sounds, BP, vascular occlusion, or cardiac contractility. These devices leverage energy harvesting mechanisms such as TENGs and PENGs to enable continuous, battery-free sensing with high sensitivity, long-term stability, and wireless data transmission. Section B focuses on therapeutic devices that not only harvest biomechanical or biochemical energy but also deliver electrical stimulation

Table 1

Representative self-powered cardiovascular devices: performance comparison and application scenarios.

A. Monitoring devices

Device	Energy harvesting mechanism	Key parameters	Signal type	Application scenario	Validation method	Advantages	References
Wearable pulse wave sensor	Piezoelectric nanogenerator	Signal-noise ratio: 45 dB	Pulse wave (PW)	Continuous PW monitoring	Clinical	High accuracy, wearable	Ouyang et al.[64]
Sleep apnea sensor	Piezoelectric nanogenerator	Accuracy: 99.59%	PW	Long-term sleep apnea syndrome monitoring	Clinical and Deep learning model	High diagnostic accuracy, practical for home use	Wang et al.[66]
PENG cardiovascular diagnosis system	Piezoelectric nanogenerator	V_{OC}: 60 mV, I_{SC}: 2 nA; Accuracy: 93.75%	Pulse waveform	Early diagnosis of common cardiovascular diseases	Clinical trials and deep learning	High sensitivity, noninvasive, suitable for long-term monitoring	Sun et al.[68]
Self-powered micro-pressure sensor	Piezoelectric nanogenerator	Voltage density 346.4 ± 115.2 V/cm^3	Pressure	Implant on heart & femoral artery	*In vivo* (pig)	Precise sensing across; thrombus diagnosis	Chang et al.[80]
Stretchable triboelectric sensor	Triboelectric nanogenerator	Force range: 0.002–300 N	PW, motion	Vital signs	Application demos	Wide sensing range, soft/stretchable	Yang et al.[69]
Vascular graft sensor	Triboelectric nanogenerator	V_{OC}: 440 V; Power density: 1877 mW/m^2 (8 MΩ)	Hemodynamic flow patterns	Postoperative vascular graft monitoring	Hemodynamic sensing	Excellent pressure sensitivity, stability	Wang et al.[65]
Heart sound sensor	Triboelectric nanogenerator	Sensitivity: 7027 mV/Pa; Detection limit: 47 dB	Heart sounds	Auscultation & CVD screening	Multisite test, signal classification	Apparel-integration; high sensitivity; stable	Li et al.[81]
Bias-free cardiac monitoring capsule	Triboelectric nanogenerator	V_{OC} ↑10 × via nanoparticle self-adsorption	Heart sounds	*In situ* cardiac contractility monitoring	*In vivo* (swine model)	Minimally invasive, continuous *in situ* monitoring	Qu et al.[4]

B. Therapy devices

Device	Energy harvesting mechanism	Key parameters	Target function	Application scenario	Validation method	Advantages	References
Self-powered VNS device	Piezoelectric nanogenerator	V_{OC}: 84 V, I_{SC}: 1.32 μA (2 kPa, 1.5 Hz)	Electrical stimulation of vagus nerve (neuromodulation)	Cardiovascular and neuropsychiatric therapy via vagus nerve stimulation	*In vivo* test on 4 canines	Self-powered, flexible	Zhang et al.[38]
Optogenetic neuromodulation system	TENG-based optical stimulator	V_{OC}: 78 V, I_{SC}: 0.7 μA	Optogenetic neuromodulation (sympathetic inhibition)	Post-MI ventricular arrhythmia and remodeling treatment	*In vivo* (ambulatory canines)	Self-powered, wireless, long-term use	Zhou et al.[39]
i-PENG system for pacemaker	Piezoelectric nanogenerator	Charges 100 μF to 4 V in 13 min	Power supply for pacemaker	Implantable CIEDs	*In vivo* (pig heart)	Fast capacitor charging; powers commercial pacemaker	Wang et al.[82]
Self-powered intracardiac pacemaker	Triboelectric nanogenerator	V_{OC}: 6 V, I_{SC}: 0.2 μA	Cardiac pacing	Implantable, right ventricle via catheter	*In vivo* (swine), 3-week follow-up	Catheter-based implantation, stable pacing	Liu et al.[74]
Self-powered biomimetic trinity TENG cardiac patch	Triboelectric nanogenerator	sensitivity 2.65 mV/1%	Cardiac electrostimulation, diagnosis, and monitoring	Implantable on infarcted myocardium	*In vivo* (rat model), RNA-seq analysis	Integrates therapy, energy harvesting, and wireless diagnosis	Qiu et al.[24]
Flexible fuel cell patch	Glucose fuel cell	Power density = 51.55 μW/cm^2	Electrostimulation and hypoxia induction for tissue repair	Implantation on peripheral nerves and myocardium	*In vivo*	Adherent, flexible; dual function: electrostimulation + hypoxia	Lin et al.[9]
Closed-loop self-powered vagus nerve stimulation	Hybrid nanogenerator (triboelectric + piezoelectric effects)	V_{OC}: 14.8 V, I_{SC}: 17.8 μA	Low-level vagus nerve stimulation for AF treatment	Intelligent, closed-loop AF monitoring and neuromodulation	*In vivo* AF model	Flexible, miniaturized, battery-free	Sun et al.[30]

AF = atrial fibrillation; CIED = cardiac implantable electronic device; CVD = cardiovascular diseases; Isc = short circuit current; MI = myocardial infarction; PENG = piezoelectric nanogenerator; TENG = triboelectric nanogenerator; Voc = open circuit voltage; VNS = vagus nerve stimulation.

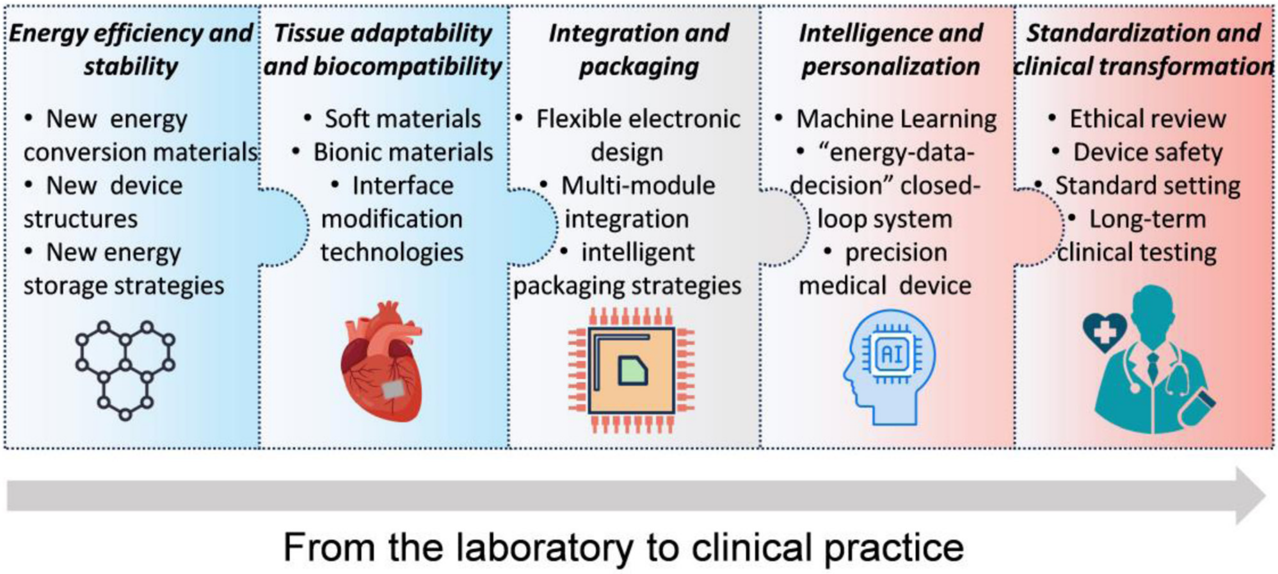

Figure 8. Key challenges and considerations for self-powered cardiovascular medical devices in key technologies and clinical transformation.

or microenvironmental regulation. These systems—ranging from self-powered vagus nerve stimulators to hybrid therapeutic patches—exemplify advanced integration of diagnosis, energy harvesting, and closed-loop therapy. The table provides a comparative overview of key technical parameters, energy harvesting strategies, application scenarios, validation models, and unique advantages of each device.

5. Conclusion and perspectives

This review focuses on the limitations of current clinical cardiovascular medical devices in terms of large size, bulky structure, and reliance on battery power supply, and focuses on the application progress of emerging self-powered technologies in cardiovascular monitoring and treatment. It systematically reviews the representative research results in this field in recent years. In general, self-powered cardiovascular medical devices are expected to break through the bottlenecks of traditional devices in terms of portability, sustainability, and remote use, potentially reshape the existing clinical intervention model, and provide a new development direction for the personalized management and precision treatment of CVDs. It is worth noting that different self-powered cardiovascular medical devices are currently clearly stratified in terms of clinical feasibility. For example, external monitoring systems represented by wearable pulse, heart sound, and BP monitoring devices are close to the clinical application stage due to their low energy consumption, noninvasiveness, and easy integration of flexible electronic devices. Prioritizing their large-scale verification and standardization will help accelerate their implementation. In contrast, although implantable self-powered cardiovascular treatment devices such as pacemakers and artificial blood vessels have shown good prospects, they still face limitations such as long-term stability verification, insufficient energy efficiency, *in vivo* packaging, and biosafety. It is necessary to focus on material upgrades, packaging technology, and energy management optimization to promote the clarification of their clinical transformation paths. Therefore, as shown in Figure 8, despite the rapid development of this field, it still faces many challenges in key technologies and clinical transformation, and it is urgent to continue to advance in energy efficiency, biocompatibility, system integration, intelligence, and standardized evaluation systems.

5.1. Energy efficiency and stability

The core of self-powered cardiovascular medical devices is to continuously and reliably obtain energy from the body or surface environment. However, the current mainstream energy conversion technologies such as TENG and PENG still have problems with low output power and limited efficiency, and it is difficult to support high-power functional modules such as wireless communication or complex signal processing. At the same time, the equipment faces challenges such as material aging, structural deformation, unstable output, and weak energy management capabilities during long-term operation. Therefore, it is necessary to develop higher performance energy conversion materials, optimize device structures, and introduce efficient energy storage and energy regulation strategies to achieve continuous, efficient, and stable power output to meet actual clinical needs.

5.2. Tissue adaptability and biocompatibility

The cardiovascular system environment is complex, and devices must have good mechanical adaptability and biocompatibility during long-term contact with tissues such as the heart and blood vessels. At present, most materials still have problems such as insufficient flexibility and large differences in mechanical matching with biological tissues, which will not only cause motion artifacts to affect data accuracy, but also easily cause adverse reactions such as local tissue inflammation, fibrosis, or displacement. To overcome this challenge, soft materials, bionic materials, degradable flexible devices, and interface modification technologies with tissue adhesion and low immune response should be further developed to improve the long-term stability and biofriendliness of the device and ensure its safe operation in the body.

5.3. Integration and packaging

Self-powered cardiovascular medical devices involve multiple functional modules such as energy collection, perception, processing, and feedback. Achieving efficient integration and reliable packaging is one of the bottlenecks in current technological development. There are differences in size, electrical performance, and flexibility requirements between different modules. How to achieve multifunctional integration without increasing the volume while maintaining stable operation of the system is an urgent problem that needs to be broken through. In addition, the packaging material must be flexible, waterproof, breathable, and biostable, which has extremely high process requirements. In the future, researchers should promote system-level flexible electronic design, adopt multilayer composite structures and intelligent packaging strategies, and achieve the unity of high integration and high reliability.

5.4. Intelligence and personalization

With the development of artificial intelligence and personalized medicine, self-powered cardiovascular medical devices should not only have basic monitoring and treatment functions, but also expand in the direction of intelligence to achieve adaptive regulation and personalized intervention. At present, some studies have tried to embed edge computing and machine learning into devices for tasks such as heart rhythm recognition and disease warning, but the overall intelligence level is still limited. In the future, the development of the "energy-data-decision" closed-loop system should be strengthened, and an intelligent platform that can dynamically adjust the response according to the patient's status should be built. At the same time, model training should be carried out in combination with individual differences to promote the transformation of equipment into a true "precision medical assistant."

5.5. Standardization and clinical transformation

Although self-powered cardiovascular medical devices have shown great potential in the laboratory, they are still far from being widely used in the clinic. The current lack of unified technical standards and evaluation systems has limited the coordinated development across institutions and disciplines. Simultaneously, most studies are still in the animal experiment or *in vitro* verification stage, lacking systematic clinical trials and long-term data accumulation. In the future, a complete transformation path from device safety assessment, ethical review to product registration should be established, and clinical research, standard setting, and policy support should be strengthened to promote self-powered cardiovascular medical devices from the laboratory to real life.

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Ethical statements

Not applicable.

Conflicts of interest

The authors have no conflicts of interest to disclose.

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Data availability statement

All data generated or analyzed during this study are included in this published article (and its supplementary information files).

Author contributions

Peng Cheng and Yuan Xi studied the data from the article and wrote the manuscript. Yang Zou and Zhou Li reviewed and revised the paper. All authors discussed the content of the article and reviewed it before submission.

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