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Flexible ultrasound patches for cardiovascular function and disease monitoring

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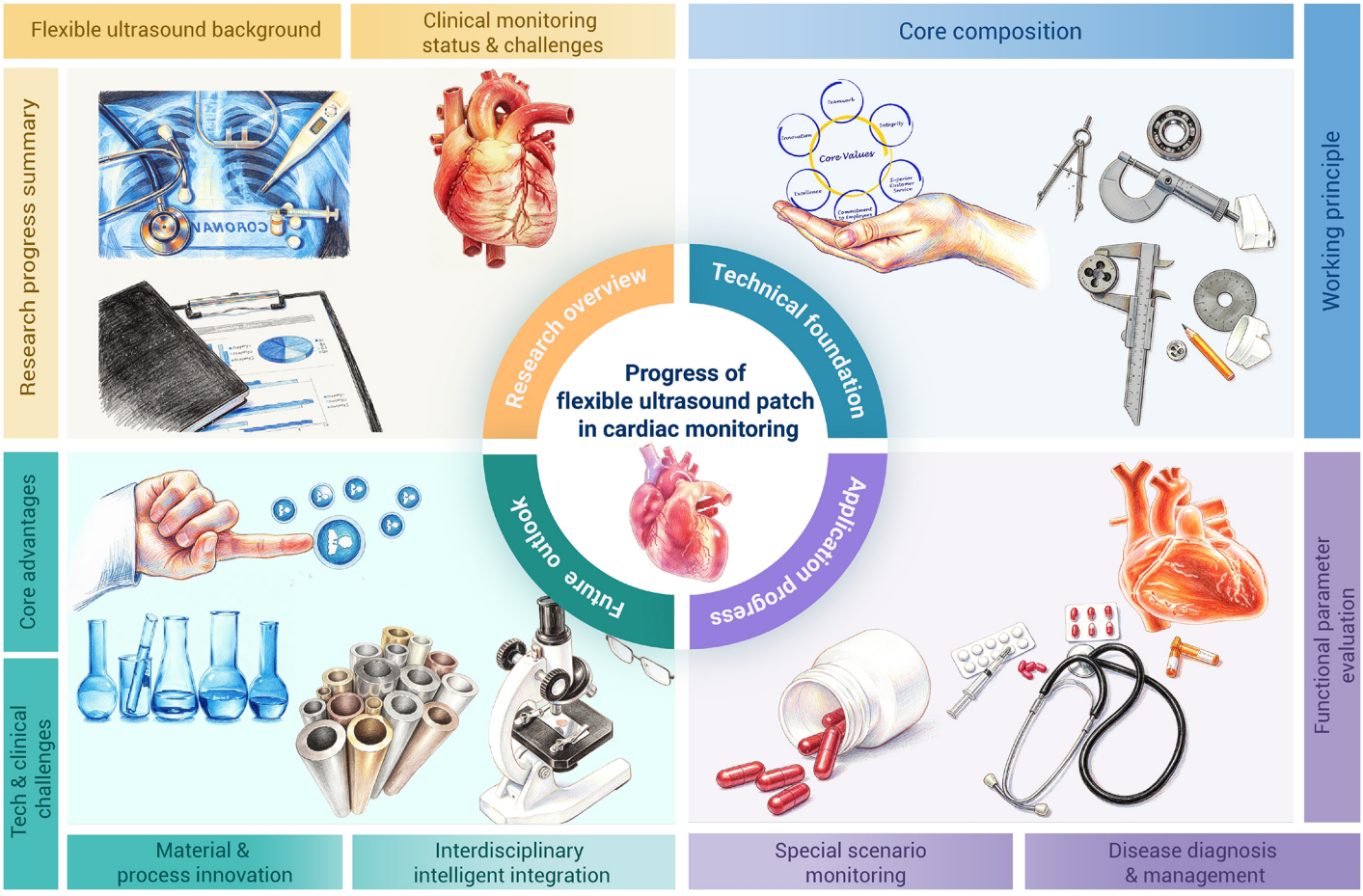
GRAPHICAL ABSTRACT



PUBLIC SUMMARY

- Cardiovascular diseases show subtle early lesions, fueling demand for real-time noninvasive circulatory monitors.
- Flexible ultrasound patches achieve long-term noninvasive detection of key cardiovascular physiological indicators.
- This review outlines the structure, mechanism and latest monitoring applications of flexible ultrasound patches.
- Analyzes key performance conflicts, suggests optimizations, and summarizes clinical industrialization hurdles.

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Cardiovascular diseases, one of the leading causes of death worldwide, often present with subtle early-stage lesions, making it imperative to obtain continuous, quantifiable circulatory physiological information in real-life settings. Flexible ultrasound patches integrate piezoelectric transducer arrays, flexible packaging, and acoustic coupling materials into an ultrathin platform that adheres to the skin. They enable long-term, noninvasive monitoring of key indicators, such as cardiac structure, hemodynamics, and vascular elasticity. This article systematically reviews the structural composition and working principles of flexible ultrasound patches, as well as their functional capabilities, including blood flow detection and tissue imaging. It further summarizes recent research progress and representative achievements in applications such as the assessment of cardiac structural and functional parameters, continuous monitoring during rest and exercise stress, and use in heart failure, coronary heart disease, cardiomyopathy, and postoperative follow-up. Offering a fresh perspective, we identify a central bottleneck: the inherent trade-off between skin conformability and acoustic performance. Based on this, we propose design principles centered on adaptive compliance, modular system architecture, and on-patch intelligent processing. We then prioritize three future directions: low-cost manufacturing, standardized clinical validation, and integration with telemedicine platforms, to guide the field. Finally, we discuss the core challenges facing their clinical translation, including limited spatial resolution, motion artifacts, long-term wear stability, algorithm development and standardization, and validation against gold-standard measurements. Future directions-including innovations in materials and manufacturing processes, intelligent algorithms and multimodal data fusion, and large-scale clinical validation-are also highlighted to promote industrialization and clinical implementation.

INTRODUCTION

Cardiovascular diseases (CVDs) represent the foremost global public health challenge of the 21st century. Their incidence and mortality rates continue to rise because of population aging, the high prevalence of metabolic disorders, and shifts in lifestyle patterns. CVD-related deaths account for one-third of all global deaths.[1] Most CVDs exhibit insidious early symptoms and chronic progression, with extremely high rates of disability and mortality during the decompensated phase. Therefore, shifting the focus of management to early prevention and risk control is essential to reduce the disease burden. This concept has become a global consensus in the cardiovascular field.[2]

With respect to early prevention and risk control, the current CVD prevention and control system is centered on "vital sign monitoring–risk identification–early intervention" and is divided into two major components: professional monitoring in clinical settings and health management at the community and family levels.[3] Clinical settings conduct risk stratification through periodic standardized examinations,[4] whereas community and family settings implement preliminary early warning strategies primarily through health education and lifestyle interventions.[5] However, the existing system has monitoring limitations that hinder its ability to meet the requirements of precise prevention and control for early-stage, asymptomatic CVDs.[6] The clinical management of CVDs has shifted from single assessments to long-term standardized follow-up. Core physiological indicators in high-risk populations often fluctuate before the onset of symptoms, which is critical for the early identification of occult disease. Therefore, it is necessary to overcome the traditional spatiotemporal constraints of monitoring by enabling continuous collection of physiological signals in real-world settings. This approach enhances monitoring convenience, ensures data continuity, and supports early and precise intervention.[7]

The current cardiovascular disease monitoring system primarily relies on a fixed-point, intermittent model, which has significant limitations. For instance, although medical institutions provide accurate monitoring, they capture only sporadic point-in-time data, making it difficult to detect intermittent abnormalities. Community-based home monitoring offers convenience but is limited in measurable parameters and data stability, thereby failing to provide clinically actionable continuous hemodynamic information.[8] Data fragmentation further hinders early risk identification and reduces the effectiveness of timely intervention. Therefore, the development of noninvasive, comfortable wearable monitoring technologies capable of assessing deep tissues and generating quantifiable metrics has become a central focus in comprehensive cardiovascular lifecycle management.

To address these core bottlenecks in cardiovascular disease monitoring, flexible ultrasound patches have emerged as a significant breakthrough in wearable monitoring technology. Owing to their key advantages—noninvasiveness, excellent biocompatibility, high skin conformability, and continuous data acquisition—they represent a promising solution to overcome the limitations of traditional monitoring approaches and to advance early detection of cardiovascular dysfunction and disease.[9] Li et al. reported a flexible ultrasound patch based on silicon nanocolumns that enabled high-resolution cardiovascular imaging and continuous blood pressure monitoring, thereby providing precise evidence for early disease screening.[10] The CPP piezoelectric array design proposed by Zang et al. significantly improved monitoring stability, meeting the demands of long-term dynamic monitoring.[11] In addition, a stretchable Doppler flexible ultrasound patch reported by Xu et al. accurately captured cardiovascular hemodynamic changes while maintaining monitoring errors within 4.1%–12%.[12] This type of flexible ultrasound patch enables continuous dynamic monitoring of cardiovascular parameters and provides reliable data support for cardiovascular function assessment and early disease detection.[13] This technology also aligns with the emerging paradigm of smart fibre-enabled fabrics and closed-loop wearable systems, where sensing, communication, data processing and energy management are integrated at the fibre/textile level.[14] In parallel, flexible electronics have emerged as a transformative platform for cardiovascular healthcare, enabling continuous, noninvasive, and patient-centric monitoring of vital signs and cardiac function.[15] Together, these studies reflect the rapid evolution of wearable cardiovascular ultrasound from stretchable transducer arrays and stable acoustic coupling strategies to wireless integration, motion-tolerant monitoring, and high-resolution patch-based imaging. To provide a chronological

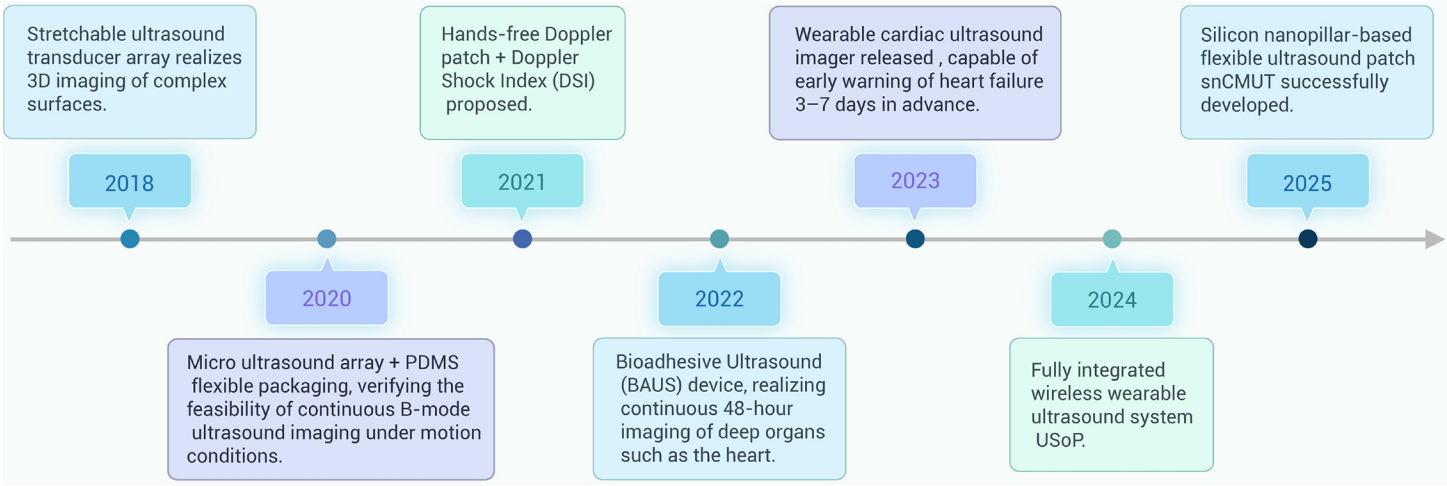

Figure 1. Key advances in wearable cardiovascular ultrasound Timeline of key milestones in flexible ultrasound for cardiovascular monitoring (2018–2025), spanning foundational stretchable transducers, motion-tolerant imaging, bioadhesive device, early heart failure warning systems, wireless integration, and next-generation nanopillar-based patches.

overview of this progress, Figure 1 summarizes representative milestones in wearable cardiovascular ultrasound, including advances in stretchable transducers, bioadhesive devices, Doppler-based hemodynamic monitoring, autonomous wireless systems, and next-generation high-resolution patch platforms. This timeline highlights the transition of flexible ultrasound patches from device-level feasibility demonstrations toward integrated systems for continuous cardiovascular function assessment and disease monitoring. Accordingly, this review systematically summarizes the core working principles and current applications of flexible ultrasound patches in cardiovascular function and disease monitoring. Furthermore, it examines the feasibility of their clinical application and the key technical bottlenecks, thereby providing a scientific reference for clinical translation and subsequent technological optimization.

This review uniquely focuses on flexible ultrasound patches dedicated to cardiovascular function assessment and disease monitoring. It systematically summarizes the full developmental context and technical evolution of such patches, from early single-function prototypes to modern multi-modal monitoring systems, and highlights three key differentiators from existing reviews: (1) an exclusive focus on cardiovascular scenarios including heart failure, coronary heart disease, cardiomyopathy, and postoperative cardiac follow-up; (2) a detailed analysis of cardiovascular-specific structural design iterations, acoustic performance optimizations, and power management strategies; (3) targeted discussion of unique technical bottlenecks in cardiac monitoring, such as motion artifact suppression, acoustic window adaptation, and long-term biocompatibility, as well as corresponding optimization directions, thus forming a clear differentiated positioning and providing a specialized reference for researchers focused on cardiovascular wearable ultrasound technology.

From our perspective, the field of flexible ultrasound patches for cardiovascular monitoring is at a critical transition from laboratory proof-of-concept to clinical reality. The most fundamental bottleneck is the trade-off between mechanical compliance and acoustic performance: highly stretchable designs degrade imaging resolution, while rigid designs compromise long-term wearability. Another key tension lies between system integration and power consumption, which limits continuous monitoring to 12–24 h. To address these challenges, we propose three design principles: (1) adaptive compliance using nanocomposite or phase-change materials; (2) modular island-bridge architectures that decouple transducer, interconnect, and coupling layers; and (3) on-patch edge AI for real-time motion artifact correction and target tracking without continuous wireless streaming. Looking ahead, we prioritize: (1) transitioning from laboratory microfabrication to high-throughput, low-cost manufacturing (e.g., roll-to-roll printing); (2) establishing standardized phantoms and clinical protocols specific to wearable ultrasound failure modes; and (3) creating closed-loop ecosystems that integrate flexible patches with telemedicine and AI-driven decision support.

COMPOSITION AND WORKING PRINCIPLES OF FLEXIBLE ULTRASOUND PATCHES

As the leading cause of death worldwide, cardiovascular disease requires continuous and precise monitoring of hemodynamics and myocardial tissue to achieve effective diagnosis and treatment. Traditional ultrasound equipment has numerous limitations and cannot meet the requirements for long-term noninvasive monitoring outside the hospital setting. Flexible ultrasound patches, owing to their skin-adherent, flexible, and highly biocompatible properties, enable real-time continuous monitoring of cardiovascular parameters and have become a research focus. The core engineering challenge lies in balancing skin-conforming flexibility with acoustic monitoring performance, which requires structural and design optimization to ensure stable and precise monitoring. This section outlines the structural composition of this technology and the function of each component. It also analyzes the fundamental principles of cardiovascular blood flow detection and myocardial imaging, thereby providing theoretical support for its research advancement and clinical translation.

The structure and composition of flexible ultrasound patches

Flexible ultrasound patches adhere closely to the skin surface, enabling continuous monitoring without spatial or temporal constraints. They primarily consist of a flexible transducer and a coupling agent. The flexible transducer typically comprises a flexible substrate, piezoelectric elements, flexible interconnect electrodes, and flexible encapsulation. Conventional flexible ultrasound patches commonly adopt an "island–bridge" structure. The "islands" are transducer units composed of piezoelectric materials that are responsible for emitting and receiving acoustic waves. The "bridge" consists of stretchable metallic electrodes that connect these islands, thereby ensuring that electrical connectivity remains intact during bending and stretching.[16] The addition of a coupling layer between the transducer and the skin facilitates efficient ultrasound transmission. Finally, the entire system is encapsulated to provide mechanical protection for the internal circuitry and to ensure close and stable adhesion to the skin (Figure 2A).

Traditional ultrasound transducers primarily employ single-element configurations for sensing or utilize multi-element arrays for imaging.[17] In recent years, an increasing number of studies have focused on structural innovations in flexible ultrasound patches through the incorporation of novel transducers and coupling agents. For instance, Hu et al. selected 1–3 piezoelectric composite materials as the active transducer material to construct a 10 × 10 piezoelectric transducers arrays. Adjacent transducer elements were spaced sufficiently apart using serpentine interconnections to enhance stretchability. By employing island–bridge electrodes encapsulated in silicone elastomer, multiple rigid elements were integrated into a stretchable transducer array capable of delivering satisfactory ultrasound imaging performance on complex surfaces, thereby enabling the continuous evalua-

tion of waveform patterns associated with central blood pressure and deep tissue hemodynamics (Figure 2B).[18] Additionally, Hu et al. employed an orthogonal piezoelectric transducer array and liquid metal composite electrodes through innovative structural design and material fabrication techniques. Mechanical coupling between the device and the skin was enhanced by encapsulation with a triblock copolymer (Figure 2C).[19] Although the island–bridge structure endows the array with stretchability, the modulus mismatch between the rigid piezoelectric units and the flexible substrate leads to stress concentration, which may cause electrode fracture or detachment of the piezoelectric elements under repeated deformation. Although liquid metal electrodes address the compatibility challenge between electrical conductivity and stretchability, their printing resolution and long-term stability remain inferior to those of conventional copper-based fabrication processes. Furthermore, reducing the thickness of the encapsulation layer to enhance flexibility may result in insufficient acoustic backing, thereby decreasing the bandwidth and sensitivity of the transducer.

Existing flexible ultrasound patch devices, whether rigid or stretchable, primarily rely on hydrogel or elastomer couplers to transmit acoustic signals to the skin. However, hydrogel coupling agents typically dehydrate or detach from the skin within hours, whereas elastomer coupling agents exhibit excessive acoustic damping, rendering them unsuitable for imaging deep-seated organs. In response, Wang et al. developed a bioadhesive ultrasound (BAUS) device consisting of a thin, rigid ultrasound probe. The probe is firmly adhered to the skin through a coupling layer composed of a soft, tough, water-resistant, and bioadhesive hydrogel–elastomer hybrid material. BAUS coupling agents comprise a soft yet resilient hydrogel formed from a chitosan–polyacrylamide cross-linked polymer network and water. This hydrogel is encapsulated within a thin polyurethane elastomer membrane to prevent dehydration (Figure 2D).[20]

In imaging applications, Kang et al. proposed a silicon nanocolumn capacitive micromachined ultrasonic transducer (snCMUT) array for real-time flexible ultrasound patch imaging in disposable patches. The snCMUT comprises individual flexible CMUT elements separated by elastomer-filled grooves, mounted on a custom-designed flexible printed circuit board, and encapsulated with polydimethylsiloxane (PDMS) (Figure 2E). This unique structure enhances displacement efficiency, thereby enabling high-resolution imaging while maintaining a slim and flexible form factor. Following successful application in monitoring both sides of the human carotid artery, the snCMUT delivered clear ultrasound images and continuous blood pressure waveform monitoring.[10] Current research on flexible ultrasound patches primarily focuses on validation at the transducer unit or array level, whereas full system integration remains at the laboratory stage. Most prototype devices rely on external commercial ultrasound platforms for data acquisition and image reconstruction and therefore have not achieved a truly plug-and-play system.

Currently, the flexible ultrasound patch materials have been innovated from traditional metal materials to biological materials. They are not only designed to stick to the skin, but also need to ensure that the material performance does not deteriorate under dynamic environments such as stretching, while also considering biocompatibility and long-term safety. The integration of lead-free piezoelectric materials, flexible electrodes, and CMUT/PMUT technology not only resolves the biocompatibility and environmental friendliness issues of traditional rigid probes, but more importantly, it paves the way for low-cost and highly consistent wafer-level mass production. This is the key prerequisite for flexible ultrasound patches to move from the laboratory to the wearable consumer market.

Working principles of flexible ultrasound patches

Principles of hemodynamic monitoring using flexible ultrasound patches. Hemodynamic monitoring represents a pivotal entry point for flexible ultrasound patches in the cardiovascular field. Compared with indirect measurement techniques, such as pressure-based or optical sensing methods, ultrasound technology offers distinct advantages, including noninvasiveness, real-time capability, and high precision. It enables direct observation of vascular wall displacement and blood flow velocity. This approach accurately reflects cardiovascular physiological status.[21] The principle of ultrasonic wave generation is based on the inverse piezoelectric effect of piezoelectric materials. An external driving unit applies a high-frequency alternating electrical signal to the transducer. When this signal is applied to the piezoelectric elements, an alternating electric field is generated within the material. This field interacts with the intrinsic polarization field, inducing periodic lattice deformation. The lattice elongates when the electric field aligns with the polarization direction and contracts when it is oriented oppositely. This high-frequency alternating electric field induces compressional vibrations within the piezoelectric material. These vibrations are transmitted to the skin through an acoustic matching layer and generate ultrasonic waves that propagate into the body. The matching layer acts as a transitional zone. By selecting specific materials, the acoustic impedance is designed to exist between the skin and the piezoelectric element, thereby enhancing the transmission rate. At the same time, the maximum energy penetration can also be achieved through thickness design by utilizing interference cancellation.

The heartbeat drives the periodic expansion and contraction of arterial vessel walls, and this deformation serves as the primary target for hemodynamic monitoring. Flexible ultrasound patches emit high-frequency ultrasound waves thousands of times per second. These waves are reflected by the vessel walls to generate echoes. The receiving unit precisely records the return time of these echoes (Figure 3A). Through algorithmic analysis of the echo time differences, micrometer-level calculations of vessel wall position and movement velocity can be achieved. The measured changes in the blood vessel diameter can be used to derive the hemodynamic parameters, such as the BP waveform, heart rate, and vascular stiffness, etc. (Figure 3B).[22] During blood flow monitoring, ultrasound waves are scattered by flowing red blood cells. The movement of red blood cells induces frequency shifts in the scattered acoustic waves, known as the Doppler effect. Analysis of this frequency shift enables measurement of parameters such as blood flow velocity and flow rate, thereby supporting disease diagnosis.[23,24]

Lin et al. developed the ultrasonic-system-on-patch (USoP), a fully integrated autonomous flexible ultrasound patch system that overcomes the limitations of traditional patches requiring external devices and enables precise monitoring of cardiovascular data during physical activity. This patch integrates an ultrasound transducer with a miniature wireless controller, resulting in a compact structure. The ultrasound transducer achieves bidirectional conversion between electrical and acoustic signals through miniature piezoelectric crystals. The control unit comprises an analog front end (AFE) and a data acquisition module (DAQ). The AFE performs ultrasonic sensing through the coordinated operation of a sequencer, pulse generator, and multiplexer. The sequencer initiates monitoring, the pulse generator delivers high-voltage pulses to activate the transducer, and the multiplexer drives the array to transmit and receive ultrasonic signals. The resulting echo signals are acquired, amplified, and filtered before being transmitted to the DAQ module. The microcontroller samples the analog signals via an analog-to-digital converter, and the Wi-Fi module wirelessly transmits the digitized data to a terminal device. The USoP features mobile target-tracking capability and can autonomously complete data acquisition and processing, thereby providing a solution for long-term monitoring of deep cardiovascular structures during motion and expanding its potential application scenarios.[25]

Principle of tissue imaging using flexible ultrasound patches. By emitting ultrasound waves and receiving echoes from tissue interfaces, combined with computer-based signal processing, this technology enables visualization of internal tissues and provides intuitive support for the diagnosis of cardiovascular lesions.[26] Clinically used ultrasound transducers are categorized into three types based on crystal array configuration and acoustic emission characteristics to accommodate different cardiovascular monitoring requirements. Linear array transducers feature a linear arrangement of crystal elements that produce parallel acoustic beams with a wide near-field field of view and high resolution, making them suitable for superficial vascular examinations. Convex array transducers are characterized by a curved crystal arrangement that generates a fan-shaped acoustic beam, providing a wide far-field field of view and strong penetration capability, and are therefore appropriate for abdominal vascular examinations. Phased array transducers achieve beam steering and focusing by controlling the transmission delay of array elements. They are particularly suitable for cardiac ultrasound examinations, enabling clear visualization of structures such as the myocardium and cardiac chambers.

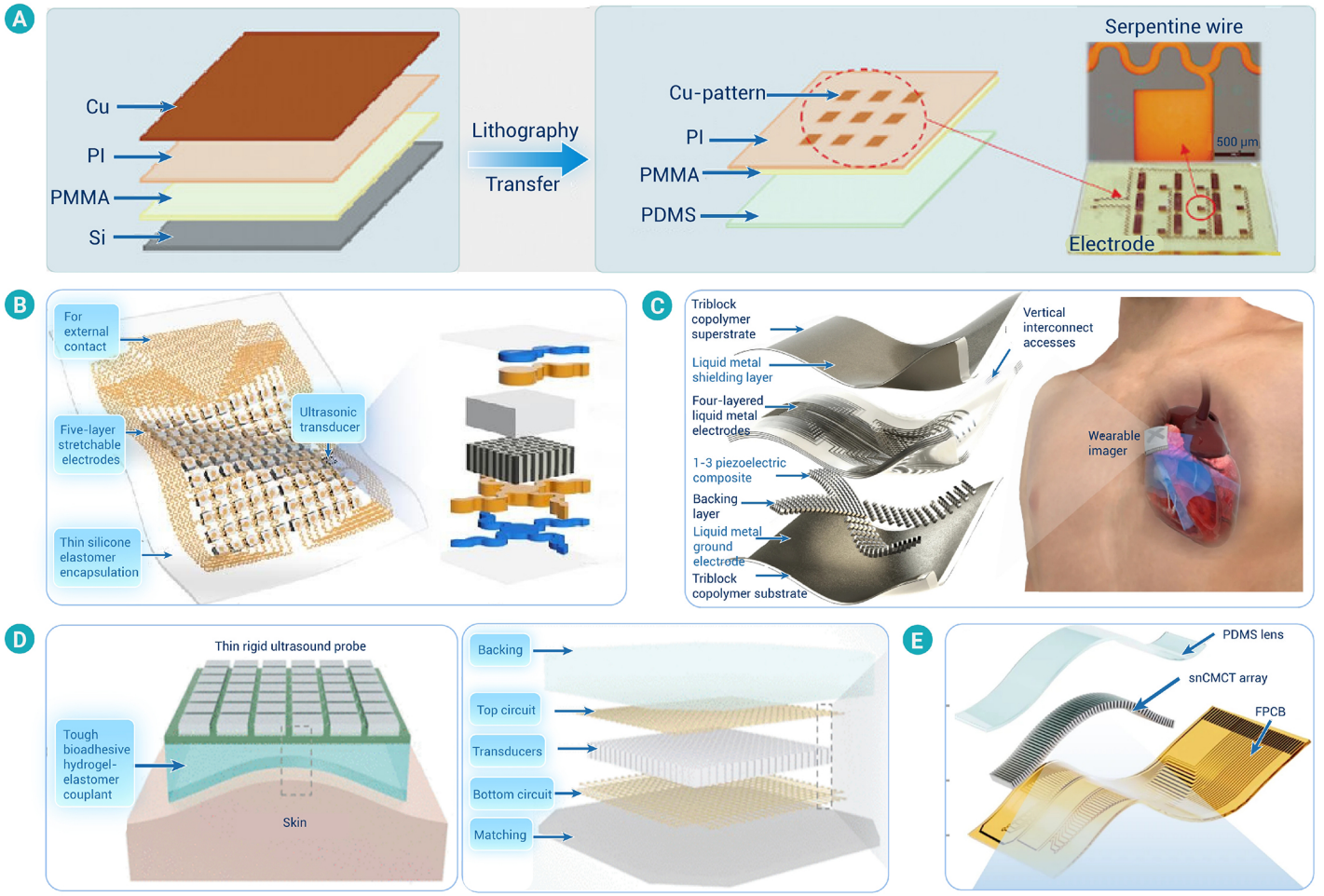

Figure 2. Structure of flexible ultrasound patches (A) Common flexible ultrasound patch structure and internal circuitry; Modified appropriately and reproduced with permission.[16] Copyright 2021, Wiley. (B) 10 × 10 piezoelectric transducers arrays; Modified appropriately and reproduced with permission.[18] Copyright 2018, American Association for the Advancement of Science. (C) Orthogonal piezoelectric array with liquid metal electrodes; Modified appropriately and reproduced with permission.[19] Copyright 2023, Nature. (D) Structure of hydrogel coupling agent; Modified appropriately and reproduced with permission.[20] Copyright 2022, American Association for the Advancement of Science. (E) snCMUT array. Modified appropriately and reproduced with permission.[10] Copyright 2025, Nature.

The core principle of ultrasound imaging lies in variations in propagation speed and acoustic impedance among different tissues, which constitute the fundamental basis of image formation. Interfaces with substantial differences in acoustic impedance, such as those between soft tissue and bone, generate strong reflected signals that clearly delineate the position and morphology of the interface. In contrast, homogeneous tissues or fluids exhibit relatively uniform acoustic impedance, resulting primarily in sound wave transmission or weak scattering and consequently weak reflected signals. By measuring the echo time and intensity of reflected sound waves and combining these data with the average propagation velocity of ultrasound in human tissue, approximately 1540 m/s, the spatial coordinates of reflective interfaces can be precisely calculated. Through electronic scanning, discrete echo information is integrated to synthesize two-dimensional or three-dimensional tomographic images, thereby clearly presenting the structure and morphology of cardiovascular tissues (Figure 3C).[27]

In the field of cardiovascular imaging optimization, Wang et al. employed stretchable phased-array ultrasound technology to synchronously control the emission timing of array transducers, thereby enhancing ultrasound energy density and enabling acoustic beam steering. This approach allows direct cardiac interrogation and analysis of myocardial dynamics, capturing the processes of myocardial contraction and relaxation. By integrating receiver-side beamforming technology to compensate for phase differences among array elements and superimposing reconstructed high–signal-to-noise ratio (SNR) echoes, imaging resolution was significantly improved, enabling clear visualization of minute lesions.[28] Hu et al. thought the transmit beamforming strategy is critical for image quality. They compared three distinct strategies: plane-wave, mono-focus and wide-beam compounding. Phantoms containing monofilament wires were used for this comparison. Among the three strategies, the wide-beam compounding implements a sequence of divergent acoustic waves with a series of transmission angles, and the generated images of each transmission are coherently combined to create a compounding image, which has the best quality with an expanded sonographic window (Figure 3D).[19] During the signal processing stage, an AFE with high input impedance, low-noise amplification, and a high common-mode rejection ratio is employed to suppress noise and amplify microvolt-level echo signals. The analog signals are converted into digital signals through anti-aliasing filtering followed by analog-to-digital conversion. Digital filtering and embedded algorithms further refine the signals and reduce the transmission load.[29] For data transmission, Bluetooth Low Energy, Zigbee, or LoRa wireless technologies are selected according to monitoring requirements. Combined with low-power strategies, such as data compression and intermittent transmission, these approaches balance device endurance and transmission reliability, thereby ensuring long-term continuous imaging of cardiovascular tissues.

In summary, flexible ultrasound patches transform ultrasound from traditional desktop-based, intermittent examinations into skin-adherent, continuous monitoring through structural flexibility and advanced acoustic processing strategies. Building on these principles, researchers have achieved significant advances in cardiac structural imaging, hemodynamic quantification, and disease risk assessment. The following sections systematically review representative studies and summarize their clinical value, with a focus on typical applications in cardiovascular function and disease monitoring.

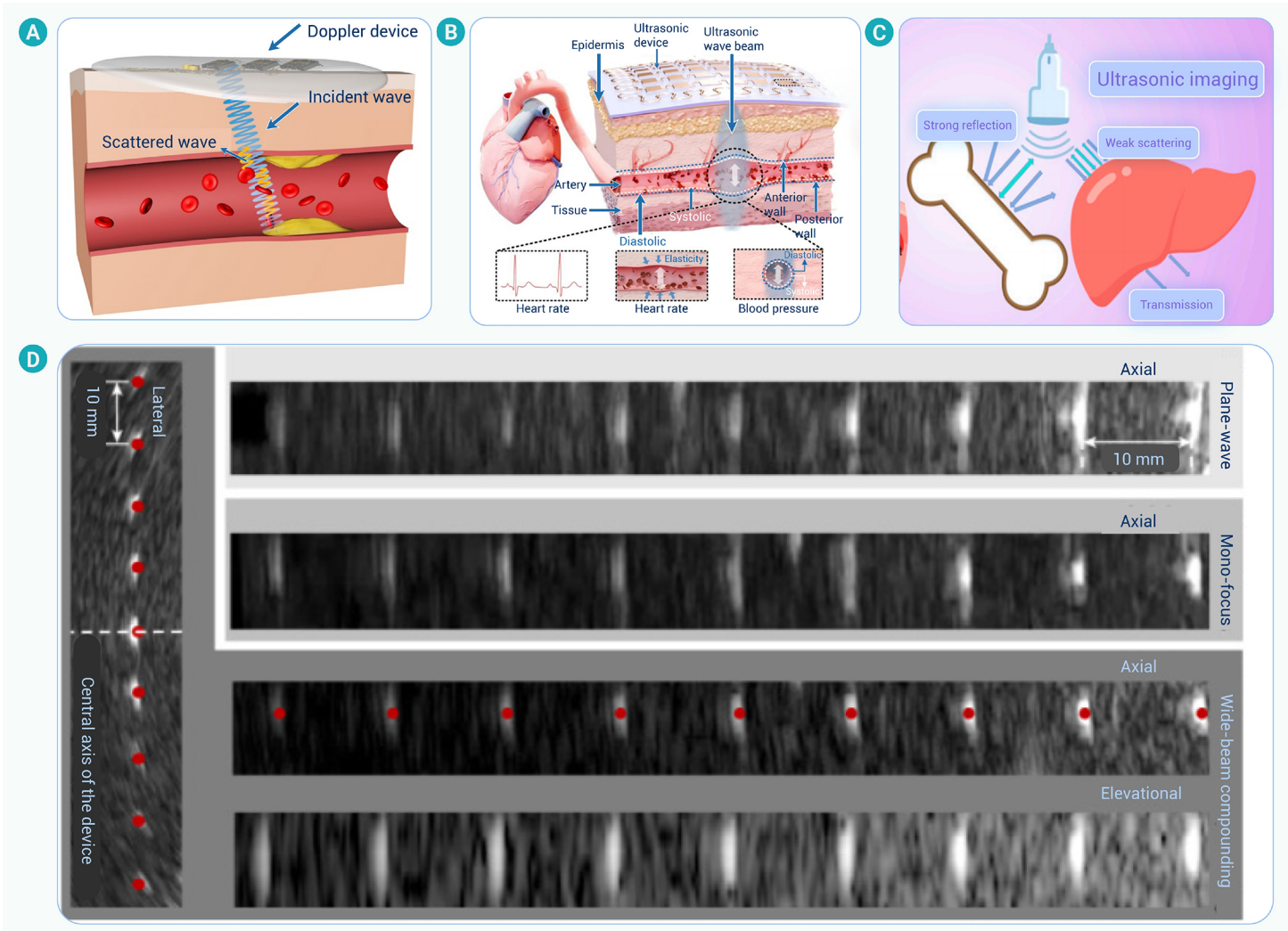

Figure 3. Working principles of the flexible ultrasound patch (A) Principle of monitoring blood flow and blood pressure in vessels; Modified appropriately and reproduced with permission.[22] Copyright 2021, American Association for the Advancement of Science. (B) Working principle of obtaining hemodynamic parameters through ultrasonic Doppler sensing; Modified appropriately and reproduced with permission.[22] Copyright 2025, American Association for the Advancement of Science. (C) Principle of imaging internal human tissues using ultrasound; Modified appropriately and reproduced with permission.[27] Copyright 2025, MDPI. (D) The comparison of three transmit beamforming strategy; Modified appropriately and reproduced with permission.[19] Copyright 2023, Nature.

In order to conduct a direct comparison of the performance of the aforementioned flexible patches, Table 1 systematically summarizes their structures and functions.

APPLICATIONS AND ADVANCES IN CARDIOVASCULAR FUNCTION AND DISEASE MONITORING

Cardiovascular monitoring requires sensing technologies with specific characteristics, including deep tissue penetration, dynamic performance, and resistance to interference. These technologies must clearly visualize cardiac and major vascular structures while reliably providing quantifiable parameters during rest, exercise, and long-term follow-up. Building on these principles, this section is organized into three dimensions: first, advances in flexible patches for cardiac structural imaging and parameter measurement; second, a review of continuous hemodynamic monitoring during rest and exercise; and third, an exploration of their role in the full-cycle management of common CVDs.

In recent years, several landmark studies have advanced flexible ultrasound patch from proof-of-concept demonstrations to continuous monitoring applications. Gao et al. proposed a hybrid patch integrating a rigid array within a flexible matrix, encapsulating a commercial micro-ultrasound array in stretchable PDMS. This design enabled continuous B-mode imaging of muscles and vessels, demonstrating the feasibility of maintaining stable acoustic coupling during exercise.[25] Building on this, Wang et al. significantly extended the capability of BAUS, employing an anti-desiccation coupling layer to stabilize the probe on the skin. This approach enabled continuous imaging of deep organs, including the heart, for up to 48 hours and captured dynamic changes in cardiac chamber volumes before and after exercise.[20] In a complementary technical pathway, Xu et al. further developed probes fabricated from intrinsically stretchable materials, thereby enhancing wear comfort while maintaining imaging performance and representing an alternative technical pathway toward material-intrinsic flexibility.[19] Collectively, these studies represent two distinct yet complementary technological approaches in the development of flexible ultrasound patches.

Building on the gradual maturation of device morphology and coupling strategies, research has increasingly shifted toward functional expansion and system integration. Li et al. developed a stretchable Doppler flexible ultrasound patch (core area approximately 2 × 4 cm) capable of stable adhesion to the skin during daily activities, thereby enabling continuous acquisition of blood flow spectra.[10] Jiang et al., with a focus on clinical translation, further proposed integrating signal processing, wireless transmission, and self-powered modules to develop wristband- or patch-shaped cardiovascular monitoring systems.[30] The core value of these advances lies in the ability of flexible ultrasound patches to enable noninvasive, continuous, and real-time monitoring of multiple critical cardiovascular parameters. Recent studies have confirmed the efficacy of this technology in monitoring dynamic blood pressure variations, with the potential to enhance healthcare delivery and predict patient outcomes across diverse settings, including home environ-

ments, outpatient clinics, cardiac catheterization laboratories, and intensive care units.[31] Against this backdrop, the following discussion focuses on the assessment of cardiac structural and functional parameters using flexible ultrasound patches.

Assessment of cardiac structural and functional parameters

Cardiac structural abnormalities constitute the pathological basis of various conditions, including valvular disease, cardiomyopathy, and congenital heart disease. Clinical echocardiography provides information on chamber dimensions, wall thickness, and valvular motion. However, conventional transthoracic echocardiographic examinations are highly operator dependent and time sensitive, making it challenging to obtain continuous cardiac imaging during patients' daily activities. The primary contribution of flexible ultrasound patches lies in extending ultrasound imaging from single-session examinations to long-term wearable monitoring, thereby creating a new opportunity to capture dynamic structural changes. Utilizing a biomimetic adhesive coupling layer, these patches achieved stable four-chamber imaging for up to 48 hours in healthy volunteers and recorded adaptive enlargement of left ventricular volume following exercise (Figure 4A).[20] Such continuous visualization capabilities may provide value for early postoperative recovery monitoring, structural correlation analysis of suspected paroxysmal events, and long-term follow-up assessment. To improve spatial resolution for resolving fine cardiac structures, Zeng et al. developed a 20 MHz wearable ultrasound array belt comprising a 128-channel piezoelectric composite on a flexible circuit substrate, achieving an axial resolution of 0.18 mm. In vivo imaging demonstrated clear B-mode visualization of the left and right ventricles in rat models (Figure 4B).[32]

However, in addition to acquiring extended temporal imaging, clinical demands for spatial resolution and quantitative measurability continue to increase. Constrained by transducer size, array aperture, and power consumption, current flexible patches generally exhibit lower spatial resolution than conventional desktop ultrasound systems, with particularly noticeable limitations in tasks such as endocardial border delineation and localized wall thickening quantification. Enhancing transducer density and effective aperture within flexible form factors while maintaining stable imaging under motion artifacts represents a critical challenge that requires urgent resolution. Accordingly, cutting-edge research in this field has advanced along two primary pathways. First, as demonstrated by Hu et al., orthogonal array designs were employed to capture multi-plane information (e.g., parasternal long-axis and short-axis views), and geometric models were used for cross-validation to improve volumetric measurement accuracy. B-mode wide-beam composite imaging, which provides a high signal-to-noise ratio and a broad field of view, was selected as the primary imaging modality to generate two-dimensional images of standard cardiac planes (Figure 4C). The device simultaneously acquired M-mode images to measure temporal variations in cardiac structures (e.g., left ventricular diameter and wall thickness) throughout the cardiac cycle (Figure 4D). These technological advances enable patients to monitor cardiac function during daily activities and facilitate the clinical translation of cardiology research. Second, as demonstrated by teams including Timmermans et al. and Wang et al., flexible electronics, such as thin-film transistor (TFT) multiplexers, or liquid metal interconnects have been employed to fabricate fully flexible arrays with higher element density, thereby advancing toward the ultimate goal of high-resolution imaging at the hardware level. Timmermans et al. achieved the first monolithic integration of a TFT multiplexing circuit based on flexible oxide semiconductors (amorphous indium–gallium–zinc oxide, a-IGZO) with a flexible ultrasound transducer array. This system substantially reduced the number of wires connecting to the rigid complementary metal–oxide–semiconductor (CMOS) chip through the TFT multiplexer. Combined with a novel log-delta analog-to-digital converter (log-delta ADC) for efficient echo signal compression, the system ultimately achieved an eightfold reduction in front-end circuitry, a 42% decrease in front-end power consumption, and a fivefold reduction in data transmission volume.[33] Meanwhile, Wang et al. employed eutectic gallium–indium alloy (EGaIn) as the liquid metal interconnect material, encapsulated within microchannels, to fabricate a fully flexible ultrasound transducer array comprising 256 elements. This liquid metal–based interconnection method demonstrated excellent electrical conductivity and mechanical stability under repeated stretching, thereby overcoming key engineering challenges associated with realizing truly electronic skin–like flexible ultrasound patches capable of covering large body surfaces and performing autonomous imaging. Collectively, these studies establish a crucial electronic foundation for the future development of low-cost, large-area, high-resolution, fully flexible ultrasound imaging patches.[34]

The advancement of cardiac ultrasound imaging technology depends on close collaboration between biomedical engineering and clinical medicine. Lin et al. investigated the application of the USoP in M-mode ultrasound to extract physiological parameters associated with myocardial contraction. By analyzing M-mode waveforms obtained from the interventricular septum and left ventricular wall, they derived left ventricular internal diameter at end-diastole and left ventricular internal diameter at end-systole, thereby contributing to quantitative cardiac research (Figure 4B). Despite these promising results, several challenges remain, including signal processing complexity, comfort during prolonged monitoring, and measurement accuracy.[25]

Overall, flexible ultrasound patches have demonstrated the capability to stably acquire cardiac structural images and extract key anatomical parameters over extended time scales, thereby providing novel tools for the screening and follow-up of structural abnormalities. Furthermore, clinical practice increasingly emphasizes temporal fluctuations in functional parameters. Dynamic changes in metrics such as cardiac output (CO) and vascular compliance during transitions from rest to stress or exercise often precede symptom onset. Consequently, enabling continuous tracking of functional parameters alongside structural imaging represents a pivotal step for flexible ultrasound patches in advancing clinical management.

To enable a straightforward comparison, Table 2 systematically summarizes the essential characteristics of state-of-the-art flexible ultrasound patch technologies for cardiac evaluation, covering measured parameters, representative approaches, developmental maturity, core value, and key challenges.

Continuous dynamic monitoring of cardiovascular function

The division of continuous cardiovascular monitoring into resting and exercise states is grounded in fundamental cardiovascular pathophysiology. Resting conditions capture baseline function and structural phenotype under minimal metabolic demand, whereas exercise stress unmasks latent abnormalities-such as stress-induced ischemia or chronotropic incompetence-that remain silent at rest. These two contexts impose markedly different requirements on flexible ultrasound patches. Resting monitoring prioritizes long-term stability and measurement fidelity over extended periods, typically 24 to 48 hours, demanding sufficient spatial resolution for accurate delineation of chamber borders and wall thickness, along with sustained skin comfort for prolonged wear. Exercise monitoring, by contrast, shifts the emphasis to motion artifact suppression and real-time responsiveness. The patch must preserve acoustic coupling during repetitive muscle contraction and body motion, track rapid hemodynamic trajectories rather than fine structural details, and accommodate elevated heart rates and blood flow velocities.[25,28] The required monitoring window shortens to minutes, matching typical exercise protocols. These differing priorities often necessitate design trade-offs: a patch well suited for overnight resting surveillance may face challenges under high-intensity interval training, whereas a device optimized for dynamic exercise may not deliver the same level of parametric stability required for serial resting EF measurement.[19,25] The following subsections review representative progress in each setting.

Dynamic monitoring of cardiovascular function at rest. Cardiac function refers to the heart's capacity to pump blood in order to meet the body's metabolic demands. Its dynamic variations serve as crucial indicators of disease progression and therapeutic response in conditions such as heart failure and coronary heart disease. The 2023 European Society of Cardiology Heart Failure Guidelines indicate that continuous monitoring of hemodynamic parameters, such as CO and stroke volume (SV), in high-risk patients facilitates early detection of volume status changes and guides drug titration, thereby reducing the risk of readmission.[35] Consequently, establishing noninvasive, continuous monitoring capabilities that encompass both resting and stress states represents a critical requirement for achieving refined management of CVDs. However, conventional transthoracic echocardiography is

Table 1. Systematic summary of structures and functions of the aforementioned flexible patches to enable direct performance comparison.

Component	Specific Materials/Structures	Functional Description	References
Flexible Substrate	PDMS, Ecoflex, Polyimide, SEBS (triblock copolymer)	Provides mechanical support and overall flexibility; enables conformal contact with skin	16,18,19
Piezoelectric/Active Layer	1–3 piezoelectric composite (PZT/epoxy), PZT-4, PZT-5A/5H	Emits and receives acoustic waves; "islands" in island–bridge structure; high electromechanical coupling for deep tissue imaging	10,16,18,19
Interconnect Electrodes	Serpentine metallic electrodes (Cu/PI)	Form the "bridges" connecting islands; maintain electrical connectivity during bending, stretching, and deformation	16,18,19
Encapsulation Layer	Silicone elastomer (Ecoflex, PDMS), triblock copolymer (SEBS), epoxy	Provides mechanical protection for internal circuits; ensures close and stable skin adhesion	16,18,19,20
Coupling Layer (Couplant)	Hydrogel (chitosan–polyacrylamide interpenetrating network), polyurethane membrane, bioadhesive layer	Facilitates efficient ultrasound transmission; prevents dehydration; provides robust bioadhesion;	16,20
Backing/Matching Layer	Silver-epoxy composite (backing), epoxy-based matching layer	Dampens ringing, broadens bandwidth, improves axial resolution; adjusts acoustic impedance to match skin	18,19
Structural Configuration	Island–bridge structure (rigid piezoelectric islands + stretchable serpentine bridges), orthogonal array design (Mills cross), snCMUTwith elastomer-filled trenches	Enables stretchability and conformability on complex surfaces; orthogonal array allows bi-plane imaging without rotating the probe; snCMUT enhances displacement efficiency for high-resolution imaging	10,16,18,19

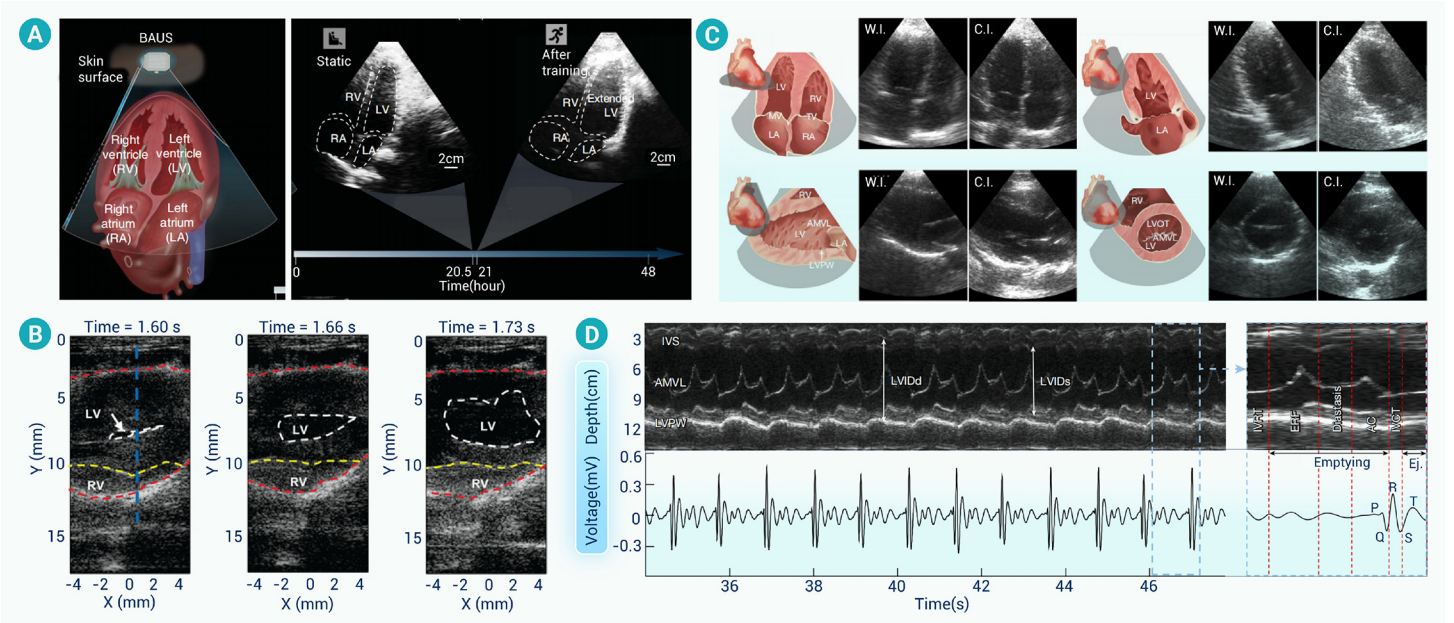

Figure 4. Monitoring cardiac structures using flexible ultrasound patches (A) Continuous dynamic imaging of the heart chambers by BAUS. Modified appropriately and reproduced with permission.[20] Copyright 2022, The American Association for the Advancement of Science. (B) In vivo B-mode images of the rat left ventricle (LV) and right ventricle (RV) captured by a wearable ultrasound array belt during the cardiac cycle. Modified appropriately and reproduced with permission.[32] Copyright 2026, Institute of Electrical and Electronics Engineers. (C) Schematic illustration of cardiac anatomy and B-mode images for multi-view and exercise monitoring. Modified appropriately and reproduced with permission.[19] Copyright 2023, Springer Nature. (D) Parameters of the heart changes during the exercise stress test. Modified appropriately and reproduced with permission.[19] Copyright 2023, Springer Nature.

constrained by operator dependence, intermittent assessment, and strict positioning requirements, making it challenging to track functional fluctuations over extended periods in real-world settings. This limitation underscores the urgent need for novel wearable ultrasound monitoring solutions.

Under resting conditions, flexible ultrasound patches have enabled continuous acquisition of core cardiac pump function metrics. Among these, systolic function parameters directly reflect ventricular pumping efficiency and form the cornerstone of disease management in conditions such as heart failure. The wearable cardiac ultrasound imaging device developed by Hu et al. employs continuous M-mode imaging to automatically track changes in left ventricular internal diameter. Combined with a deep learning model, the system reconstructs left ventricular volume waveforms from extended imaging sequences to calculate parameters including end-diastolic volume (EDV), end-systolic volume, SV, CO, and left ventricular EF. The results demonstrated good agreement with commercial ultrasound systems in terms of mean values and variability ranges (Figure 5A).[19] The significance of this approach lies in transforming a single numerical value obtained from traditional examinations into a continuous physiological waveform, thereby providing a foundation for assessing intraday fluctuations and longitudinal trends.

Beyond overall pumping capacity, preload-sensitive indicators provide unique value for evaluating volume status and guiding fluid management. Kenny et al. systematically elucidated the pivotal role of corrected flow time (ccFT or FTc)—a heart rate–corrected ventricular ejection time—in functional hemodynamic monitoring. Their findings demonstrated a complementary relationship between ccFT and velocity–time integral (VTI), with the two parameters together forming an effective tool for SV assessment (Figure 5G).[36] This perspective was robustly validated in a large-scale study by Hofer et al. Using wireless Doppler patches, they collected ccFT data from the carotid artery across more than 137,000 cardiac cycles in 347 participants.

Table 2. Comparison of technology types for flexible ultrasound patches in cardiac assessment (with references).

Technology Type	Measured Parameters	Representative Methods	Key Performance Metrics	Core Value	Key Challenges	References
Piezoelectric transducer & array	Ventricular volume, ejection fraction (EF), wall thickness, chamber diameter	1-3 composite, orthogonal array, silicon nanocolumn CMUT, liquid metal electrodes	Axial resolution: 0.19–0.77 mm; Depth:—; Accuracy:—; Response time:—; Wear duration: < 24 h	High-density, conformal, multi-plane imaging	Stress concentration at rigid-flex interface, consistency, lower piezoelectric coefficient	18,19,10,20
Coupling & encapsulation	Image continuity, signal stability, penetration depth	Bioadhesive hydrogel-elastomer hybrid, anti-dehydration membrane, silicone encapsulation	Wear duration: up to48h; Depth: —; Accuracy: —; Response time: —	Gel-free, long-term stable coupling, reduced motion artifacts	Skin irritation, acoustic attenuation, hydrogel durability	18,21
Flexible circuit & wireless system	Continuous BP waveform, HR, CO, VTI	Flexible PCB, TFT multiplexer, log-delta ADC, wireless control chip	HR accuracy: < 0.02 bpm; Power: < 614 mW; Data rate: reduced 5×; Wear duration: up to 12 h	Reduced front-end circuits and data load, wireless continuous monitoring	Power consumption, heat dissipation, battery life, integration level	25,33
Imaging & signal processing	Wall motion velocity, strain, AIx, arterial stiffness	M-mode, B-mode wide-beam compounding, phased-array beamforming	Axial resolution:0.64 mm; Frame rate: —; SNR: —; Response time: real-time	High frame rate, high SNR, quantitative analysis	Motion artifacts, phase aberration correction, lack of standardization	19,28
AI & automation	LV volume, EF, automatic channel selection, target tracking	Deep learning segmentation (FCN-32), domain adaptation (CORAL), VGG13 classification	Diagnostic accuracy: >91% (for atrial fibrillation, myocardial infarction, and heart failure)	Automated parameter calculation, moving target tracking, reduced operator dependence	Generalizability, few-shot transfer learning, edge computing	17,25

They established a physiologically plausible range of 100–500 milliseconds, noting that values outside this range were more likely attributable to signal artifacts than to true physiological states. These findings provide a solid data foundation for the clinical application of ccFT as an alternative indicator of left ventricular ejection time.[36] Kenny et al. further developed a hands-free continuous-wave Doppler flexible ultrasound patch that adheres to the neck and continuously tracks carotid artery blood flow spectra. During passive leg raising tests, the patch captured increases in carotid VTI that were synchronized with changes in aortic VTI, suggesting that carotid Doppler may serve as a noninvasive alternative approach for assessing SV dynamics.[23] This technological pathway has progressed to multicenter clinical validation, with its core contribution extending functional hemodynamic monitoring beyond the intensive care unit to general wards and even home environments.

Furthermore, cardiovascular monitoring necessitates simultaneous characterization of cardiovascular coupling parameters, such as vascular afterload and vascular elasticity. The flexible Doppler ultrasound device developed by Wang F. et al. accurately identifies multiple characteristic points in the carotid blood flow spectrum, including the first systolic peak (PSV, i.e., S1), the second systolic peak (S2), the diastolic trough (D), and the end-diastolic velocity (EDV). Based on PSV and EDV, the device calculates the resistance index RI = (PSV − EDV)/PSV to quantify vascular resistance as a surrogate of afterload. The device demonstrated measurement accuracy highly consistent with that of commercial ultrasound systems for key parameters, including PSV, EDV, time-averaged peak velocity, and the derived metric RI (Figure 5B).[22] Wang C. et al. utilized a stretchable phased-array system to simultaneously acquire blood flow velocity and vessel diameter in the carotid arteries and jugular veins. Typical pulsatile patterns were clearly discernible in the Doppler spectra, validating the feasibility of continuous blood flow monitoring in deep tissues (Figure 5C).[22] To further enhance the temporal resolution of waveform details, Vostrikov et al. proposed the TinyProbe, a 32-channel wireless platform. By employing a pulse repetition frequency of up to 1400 Hz, the system enables high-density sampling of PSV and EDV, thereby providing higher-quality raw data for more robust calculation of parameters such as RI (Figure 5D).[31]

At the vascular functional level, the self-adhesive stretchable acoustic field ultrasound (SAFU) array developed by Yuan et al. not only reconstructs beat-by-beat blood pressure waveforms but also extracts subtle features, such as the dicrotic notch and tidal waves, from arterial diameter dynamics. It further calculates the arterial stiffness index β and pulse wave velocity (PWV), thereby offering a flexible ultrasound solution for continuous noninvasive assessment of arterial stiffness (Figure 5H).[30] Wang C. et al. further synchronized the flexible ultrasound patch with electrocardiography (ECG), utilizing the time interval between the ECG R wave (representing the onset of ventricular electrical activation) and the arterial wall expansion detected by ultrasound (representing pulse wave arrival). This approach enabled PWV calculation along the brachial, radial, and dorsalis pedis arterial pathways and facilitated reconstruction of central blood pressure waveforms. Notably, the device also records jugular venous A waves (atrial contraction), C waves (ventricular contraction), and V waves (atrial filling), thereby providing a direct method for assessing right ventricular function.[24] Paul van Neer et al. optimized the transducer structure using thermal embossing and foil lamination techniques. In phantom studies, they validated the system's capability to track vascular wall motion using cross-correlation algorithms, estimate the stiffness parameter α, and subsequently convert it into a continuous blood pressure waveform P(t) (Figure 5E).[37] Lin et al. further revealed the complexity of traditional indices. By synchronously measuring the augmentation index (AIx) and local arterial stiffness index β during motion, they observed a significant increase in AIx while β remained stable. This finding demonstrated that variations in AIx primarily resulted from motion-induced peripheral vasodilation leading to displacement of reflection sites, rather than real-time changes in intrinsic arterial stiffness. These results highlight the importance of directly measuring structural parameters such as β.[25] This study provides important methodological insights for precise application of flexible ultrasound patches under complex physiological conditions; however, it primarily represents mechanistic validation rather than technological translation. Beyond comparative analyses across different age groups, the clinical feasibility of continuous blood pressure monitoring in resting subjects has been validated by Kang et al. using silicon nanocolumn-based capacitive micromachined ultrasonic transducer (snCMUT) patches. The disposable snCMUT patches incorporate lead-free design and achieve high transmission efficiency (220 kPa/V) with an ultra-thin form factor (~900 μm). Attached bilaterally to the neck in healthy volunteers, the patches simultaneously monitored both carotid arteries under resting conditions. Through M-mode imaging, the carotid artery wall motion was continuously tracked and converted into blood pressure pulse waveforms, achieving over 96.5% agreement with a clinical-grade tonometer (Figure 5F)[10], thus demonstrating the reliability of this wearable platform for accurate hemodynamic assessment in real-world settings.

Moreover, functionally derived indices that integrate heart rate and blood

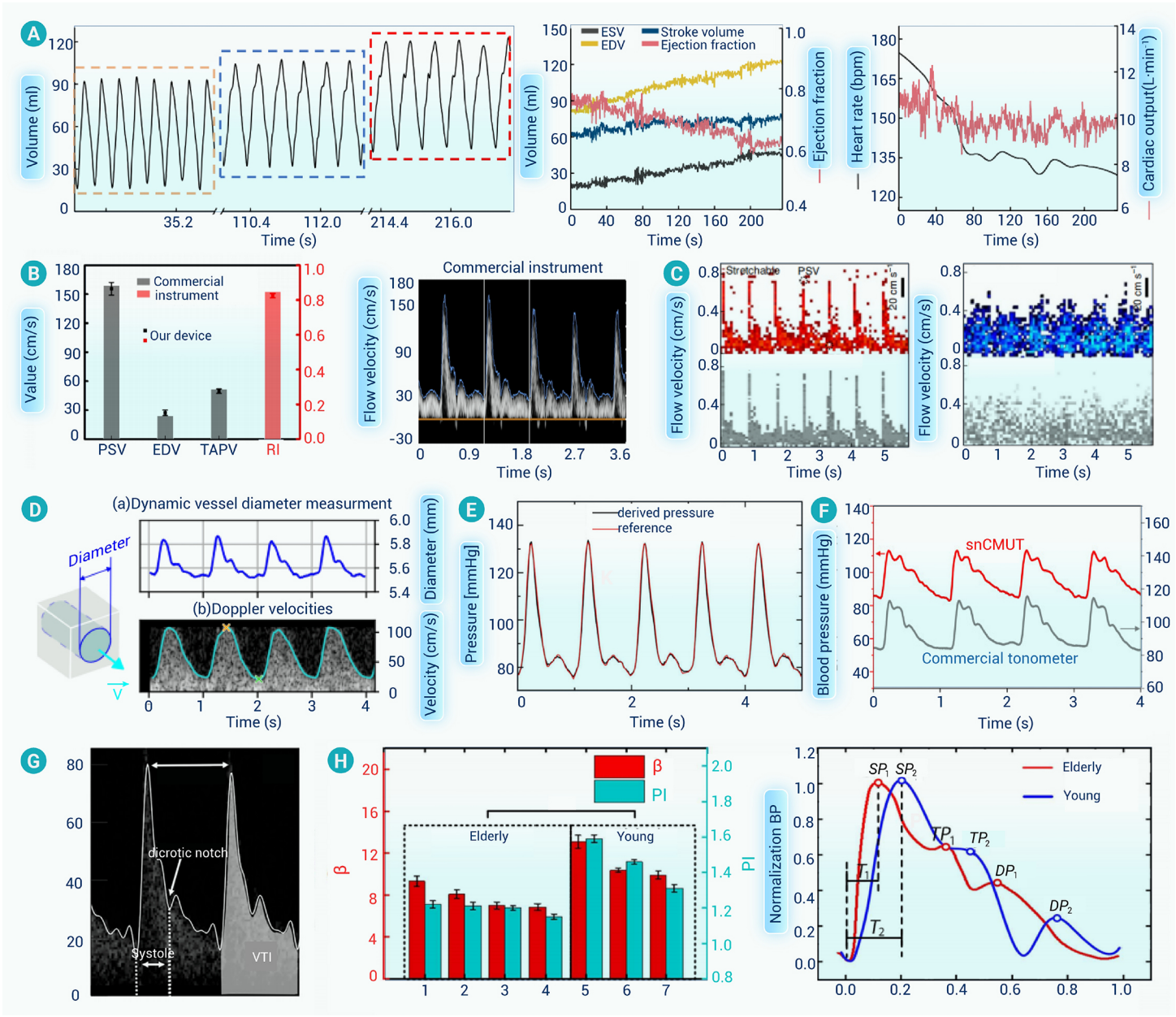

Figure 5. Monitoring cardiovascular function at rest (A) The cross-sectional diagrams of the left ventricular volume waveform at different times and the curves of other cardiac function parameters. Modified appropriately and reproduced with permission.[19] Copyright 2023, Springer Nature. (B) The key blood flow parameters calculated by the patch monitoring were compared with the measurement results obtained by commercial ultrasound systems. Modified appropriately and reproduced with permission.[22] Copyright 2021, American Association for the Advancement of Science. (C) Comparison of blood flow spectra of the carotid artery (left) and the jugular vein (right) using wearable devices and commercially available rigid ultrasound systems. Modified appropriately and reproduced with permission.[22] Copyright 2021, American Association for the Advancement of Science. (D) Imaging of wall-free channels in a fluidic model. Modified appropriately and reproduced with permission.[31] Copyright 2021, W. B. Saunders Company. (E) Pressure waveform derived from the measured diameter of a carotid vessel model over time. Modified appropriately and reproduced with permission.[37] Copyright 2024, Springer Nature. (F) Continuous blood pressure waveform monitoring of carotid artery using a disposable snCMUT patch in healthy volunteers under resting conditions, demonstrating > 96.5% agreement with a clinical-grade tonometer. Modified appropriately and reproduced with permission.[10] Copyright 2025, Springer Nature. (G) Correlating the relationship between flow time (FTc) and velocity-time integral (VTI). Modified appropriately and reproduced with permission.[36] Copyright 2021, W.B. Saunders Company. (H) Comparative analysis of β and pulsatility index (PI) between elderly and young individuals. Modified appropriately and reproduced with permission.[30] Copyright 2025, American Association for the Advancement of Science.

flow parameters provide concise and sensitive tools for assessing circulatory compensatory capacity. Kenny et al. developed a novel Doppler shock index (DSI = HR/VTI) based on common carotid artery velocity–time integral (VTI). During the Valsalva maneuver, which induces alterations in circulatory compensation in healthy volunteers, DSI captured the imbalance process with 100% sensitivity, outperforming isolated blood pressure measurements and traditional shock indices.[38] This finding is physiologically supported by earlier work from Skytioti et al., who demonstrated that SV and internal carotid artery blood flow exhibit high sensitivity to simulated hypovolemia and noninvasive ventilation. These results confirm that carotid blood flow serves as a reliable window for functional hemodynamic monitoring.[39] As a representative flexible ultrasound patch–derived metric, the core value of DSI lies in elevating continuous blood flow monitoring from parameter recording to event alerting. After preliminary feasibility validation, this metric now requires evaluation in real clinical settings, such as emergency departments and perioperative care units, to determine its predictive validity and its utility in guiding interventions.

Although the aforementioned advances demonstrate the substantial potential of flexible ultrasound patches for multiparameter fusion monitoring, most platforms—including TinyProbe—have not yet fully demonstrated real-time processing of raw signals with direct output of clinically actionable parameters, such as RI, PWV, and DSI. Future research should therefore

focus on embedded algorithm optimization and integration of edge computing to achieve a true closed-loop transition from continuous data acquisition to instantaneous clinical decision support. To provide a clearer comparison of representative flexible ultrasound patch platforms for resting-state cardiovascular monitoring, Table 3 summarizes their monitored functions, core technologies, maturity levels, technical advantages, key challenges, and major performance parameters

Cardiac function monitoring under exercise stress. Dynamic monitoring of cardiac function under exercise load represents a core technical component of cardiovascular health assessment and exercise safety management. Flexible ultrasound patches, leveraging technological advantages such as wearability and high biocompatibility, have emerged as a major research focus in this field. These devices enable continuous and precise capture of cardiovascular physiological parameters during exercise, thereby providing novel technical approaches and research paradigms for accurate evaluation of exercise-related cardiovascular function.[40,41]

Yuan et al. developed a continuous cardiac function monitoring solution for exercise-induced conditions based on a stretchable active flexible ultrasound (SAFU) sensor array.[30] This system enables real-time reconstruction of heart rate and beats-by-beat blood pressure waveforms during standardized exercise protocols, such as squats, single-arm dumbbell presses, and short-distance running, thereby comprehensively capturing the dynamic physiological process from exercise-induced elevation to return to baseline. Figure 6 summarizes the implementation workflow and representative experimental results of this monitoring system under exercise conditions. The data indicate that, compared with sedentary individuals, athletes exhibit faster chronotropic responses at exercise onset, while demonstrating significantly lower peak heart rates and more rapid post-exercise heart rate recovery. These findings indicate a functional advantage in CO associated with long-term systematic training. Statistically significant differences were observed among exercise types in the magnitude of increases in heart rate and systolic blood pressure, as well as in recovery times. Squatting induced the highest cardiovascular load and required the longest physiological recovery period after exercise. Previous studies have demonstrated that prolonged recovery times of heart rate and blood pressure are positively correlated with the risk of CVDs, such as hypertension, impaired glucose metabolism, and heart failure.[42] Further beat-by-beat blood pressure waveform analysis enables extraction of multiple integrative physiological indicators, including systolic pressure plateau delay, reverse shock index, and AIx. These metrics quantify the dynamic response characteristics of autonomic nervous system function and vascular compliance. Collectively, this research achieves synchronous acquisition and analysis of heart rate, blood pressure, and waveform characteristics on a single patch-based platform, thereby providing quantifiable and reproducible physiological evidence for precise exercise risk stratification and the scientific formulation of individualized exercise prescriptions (Figures 6A-C).

Lin et al. further validated the hemodynamic monitoring performance of flexible ultrasound patches under long-term, free-movement conditions.[25] The flexible ultrasound patch they developed, the USoP, precisely tracks carotid wall displacement using high-frame-rate imaging technology without fixed cable constraints, thereby enabling continuous and stable reconstruction of pressure waveforms. Under two typical exercise loads—30 minutes of aerobic cycling and high-intensity interval training (HIIT)—the pressure waveforms captured by the patch exhibited characteristic differences in amplitude, period, and waveform width. These variations directly reflect rapid adjustments between central circulatory capacity and peripheral vascular resistance. Using the same pressure waveform data, the researchers applied pulse contour analysis to estimate SV and CO on a beat-by-beat basis. Experimental results demonstrated that HIIT induced higher peak SV and maximal CO compared with aerobic cycling. This study established the technical feasibility of integrated beat-by-beat pressure–volume–flow analysis, thereby providing continuous and reliable physiological parameter support for optimizing individualized exercise prescriptions and dynamically assessing exercise-related risks.[43]

Wang et al. reported that BAUS imaging reveals an enlargement of jugular vein diameter when subjects shift from a sitting to supine posture. Since variations in jugular venous caliber are strongly correlated with right atrial pressure, this imaging marker facilitates the auxiliary diagnosis of cardiac disorders including heart failure and pulmonary arterial hypertension. Moreover, the BAUS platform enables 48h continuous monitoring of carotid arteries to acquire real-time blood flow velocity and blood pressure waveform data. Taking a 0.5 h jogging exercise as an example, the carotid blood flow velocity rises from 65 cm/s to 117 cm/s, while systolic blood pressure elevates from 115 mmHg to 168 mmHg after exercise. The post-exercise blood pressure waveforms exhibit a steeper descending slope of systolic peak pressure within each cardiac cycle relative to the pre-exercise counterparts, which is presumably attributed to exercise-triggered carotid vasodilation (Figures 6D-E).[20]

In summary, flexible ultrasound patches have achieved continuous and precise acquisition and analysis of heart rate, blood pressure, and hemodynamic characteristics across two critical physiological conditions: at rest and under exercise load. These advances provide robust data support and technical assurance for translating cardiovascular functional parameters into clinically meaningful disease risk signals.[40] The core breakthrough in current research lies in enabling real-time, wireless, and precise monitoring of cardiovascular parameters during exercise. This advancement overcomes the reliance of traditional ultrasound equipment on fixed monitoring environments and expands the application scope of ultrasound technology in dynamic physiological monitoring. The next research priority is to establish explicit causal mechanisms linking these continuously monitored parameters to the onset, progression, and prognosis of common CVDs. This will require construction of interpretable and generalizable indicator systems for early disease warning, diagnostic support, and assessment of therapeutic efficacy, thereby advancing the clinical translation and large-scale implementation of flexible ultrasound patches in precision cardiovascular monitoring. The following sections focus on representative cardiovascular diseases and detail the specific progress achieved in applying flexible ultrasound patches for continuous dynamic disease monitoring.

Continuous dynamic monitoring of CVDs

CVDs often exhibit chronic progression with atypical early symptoms, while disease fluctuations and acute events may occur within a short time frame.[44] Consequently, continuous monitoring and dynamic management across the continuum of screening, risk stratification, and treatment follow-up are required.[30] Flexible ultrasound patches enable long-term, noninvasive acquisition of cardiac structural, pump function, and hemodynamic data while providing excellent skin adhesion and biocompatibility. They hold promise for early warning, diagnostic support, therapeutic efficacy assessment, and post-operative follow-up in conditions such as heart failure, coronary artery disease, and cardiomyopathy, thereby offering novel technical approaches for real-world, full-cycle cardiovascular management.

Heart failure. Heart failure is a clinical syndrome resulting from the combined effects of myocardial injury, cardiac overload, ventricular remodeling, and other etiologies. These factors lead to progressive deterioration of myocardial systolic and diastolic function, significantly reducing cardiac pumping capacity and rendering it insufficient to meet the metabolic demands of systemic tissues and organs. Disease progression is characterized by an insidious course and a high risk of acute decompensation. Early and precise warning, together with continuous dynamic monitoring, is critical for delaying disease progression and reducing mortality.[35,45,46]

Clinical needs and limitations of traditional monitoring techniques. Heart failure has emerged as a major cardiovascular disease that poses a serious threat to global public health, characterized by high incidence, readmission rates, and mortality. In patients with chronic heart failure, frequent clinical fluctuations occur,[47] and acute exacerbations are often difficult to predict. Early identification of deteriorating cardiac function and timely intervention to prevent further pathological progression have become core clinical requirements for standardized heart failure management.[48] From a clinical perspective, heart failure monitoring should encompass three critical dimensions: continuous quantitative assessment of core cardiac function indicators; early detection of subclinical pathological changes, such as pulmonary congestion; and dynamic follow-up of treatment efficacy and disease fluctuations. Collectively, these dimensions form the essential basis for comprehensive heart failure management and provide indispensable guidance for clinical pharmacotherapy, optimization of treatment regimens, and improvement of

Table 3. Representative flexible ultrasound patch devices and their functional and parametric comparison for resting-state cardiovascular monitoring.

Parameter/Function	BAUS	USoP	Stretchable Doppler patch	Wearable phased array
Monitored Functions/Indices	Continuous imaging of multiple organs (heart, vessels, lung, diaphragm)	BP, HR, CO, carotid artery tracking	Continuous blood flow velocity monitoring	Cardiac phased-array imaging
Core Technology	Bioadhesive hydrogel-elastomer hybrid couplant	Fully integrated wireless system; deep learning-based automatic channel selection; domain adaptation	Symmetric dual-element array; pre-angled flexible substrate; slow-time sampling algorithm	Rubber-metal composite backing; multi-channel phased transmit/receive
Maturity Level	Preclinical / early clinical	Commercialization/clinical validation	Commercialization/clinical validation	Preclinical / early clinical
Core Value	Gel-free, 48-hour continuous imaging; anti-dehydration; good impedance matching	Wireless, wearable; 12-hour continuous monitoring; automatic moving target tracking	Lightweight (~2 g), stretchable (30%); avoids angle correction	High bandwidth (72%), high axial resolution; suitable for dynamic cardiac imaging
Key Challenges	Hydrogel durability; potential skin irritation	High power consumption (~614 mW); heat dissipation; model generalizability	Velocity error varies with angle; periodic calibration needed	High system complexity; high power consumption
Center Frequency	3, 7, 10 MHz	2, 4, 6 MHz	5.05 MHz	2.7 MHz
Axial Resolution	0.77 / 0.225 / 0.192 mm	~600 / 330 / 230 μm	—	0.64 mm
Penetration Depth	—	164 mm (2 MHz)	—	—
Elements/Channels	128 channels (BAUS-E)	—	6 (two symmetric groups)	64 elements
Size/Weight	Stamp-sized; 3 mm thick; 10-40 g	Stamp-sized	Core area 2×4 cm	2 mm thick
Measurement Error/Accuracy	—	HR difference 0.013 bpm	Velocity error 4.1%-12% (20-100 cm/s)	—
References	20	25	10	28

long-term patient outcomes.[49]

Current routine clinical heart failure monitoring technologies exhibit substantial limitations and fail to meet modern demands for precision, continuity, and home-based monitoring.[50] Echocardiography, a widely used method for cardiac function assessment, permits only single, intermittent in-hospital measurements. It cannot capture subtle fluctuations or early abnormalities in cardiac function during patients' daily activities and may therefore overlook early signs of deterioration. Biomarker tests, such as B-type natriuretic peptide (BNP) and N-terminal pro–B-type natriuretic peptide (NT-proBNP), require invasive blood sampling. This not only causes patient discomfort but also precludes real-time, dynamic, and long-term monitoring. Conventional vital sign monitoring reflects only basic parameters, such as heart rate, blood pressure, and respiration, and lacks the capacity to quantify specific cardiac function indices, including EF, myocardial strain, or pulmonary congestion. As a result, early warning may be significantly delayed. Traditional wearable devices monitor only basic metrics, such as heart rate and activity level, and lack precise imaging data on cardiac structure and hemodynamics, thereby failing to provide reliable support for early heart failure risk detection.[51] These technical limitations directly hinder clinical identification of high-risk patients before symptom onset and contribute to persistently high rates of acute decompensated heart failure. Consequently, the development of noninvasive, wearable, continuously imaging flexible ultrasound monitoring technology has become a crucial direction for overcoming current clinical monitoring challenges in heart failure. Flexible ultrasound patches, with their high adaptability, stability, and real-time imaging capabilities, offer a novel technical solution for early warning and comprehensive disease management in heart failure.[52]

Breakthroughs in core technologies and clinical application progress. Addressing clinical challenges in heart failure monitoring, flexible ultrasound patch technology has undergone iterative optimization and achieved multiple core breakthroughs in device integration, monitoring dimensions, signal analysis, and clinical application. These advances have progressively established a comprehensive technical framework evolving from single-parameter monitoring to integrated cardiopulmonary assessment. Relevant clinical studies provide robust evidence-based support for its application.[13]

At the core technology research and development level, flexible wearable cardiac ultrasound imaging devices have achieved key breakthroughs. Research in this field has established systematic empirical validation. In 2023, Hu 's team published a study in Nature demonstrating that wearable cardiac ultrasound imaging devices can accurately monitor core cardiac function indicators, such as EF and SV. By continuously tracking declining trends in these metrics, the devices can demonstrates in a small cohort the ability to track declining EF trends, suggesting a potential for early warning, pending prospective validation, such as dyspnea or fatigue, thereby providing a valuable time window for clinical decision-making.[19] To address pulmonary congestion-an early and often subclinical indicator of heart failure progression-Lin's team reported a fully integrated wearable ultrasound system in Nature Biotechnology (2024), providing critical technological support. Through in-depth analysis of ultrasound signal variations, this system enables early identification and quantitative assessment of pulmonary congestion. Clinical data demonstrated a detection sensitivity for pulmonary congestion, effectively reducing progression to acute decompensated heart failure and lowering the incidence of such high-risk events.[25] This real-time monitoring approach dynamically reflects fluctuations in cardiac function and provides precise data to support clinical evaluation of therapeutic efficacy and timely adjustment of medication regimens. Its monitoring indicators encompass multiple core parameters, including EF, SV, pulmonary venous blood flow velocity, and myocardial strain rate, thereby forming a comprehensive cardiac function assessment framework.

In clinical application and parameter system development, flexible ultrasound patches enable multidimensional cardiac function assessment. They simultaneously acquire multiple parameters, including EF, SV, pulmonary venous blood flow velocity, and myocardial strain rate. These measurements comprehensively cover key assessment dimensions, including cardiac

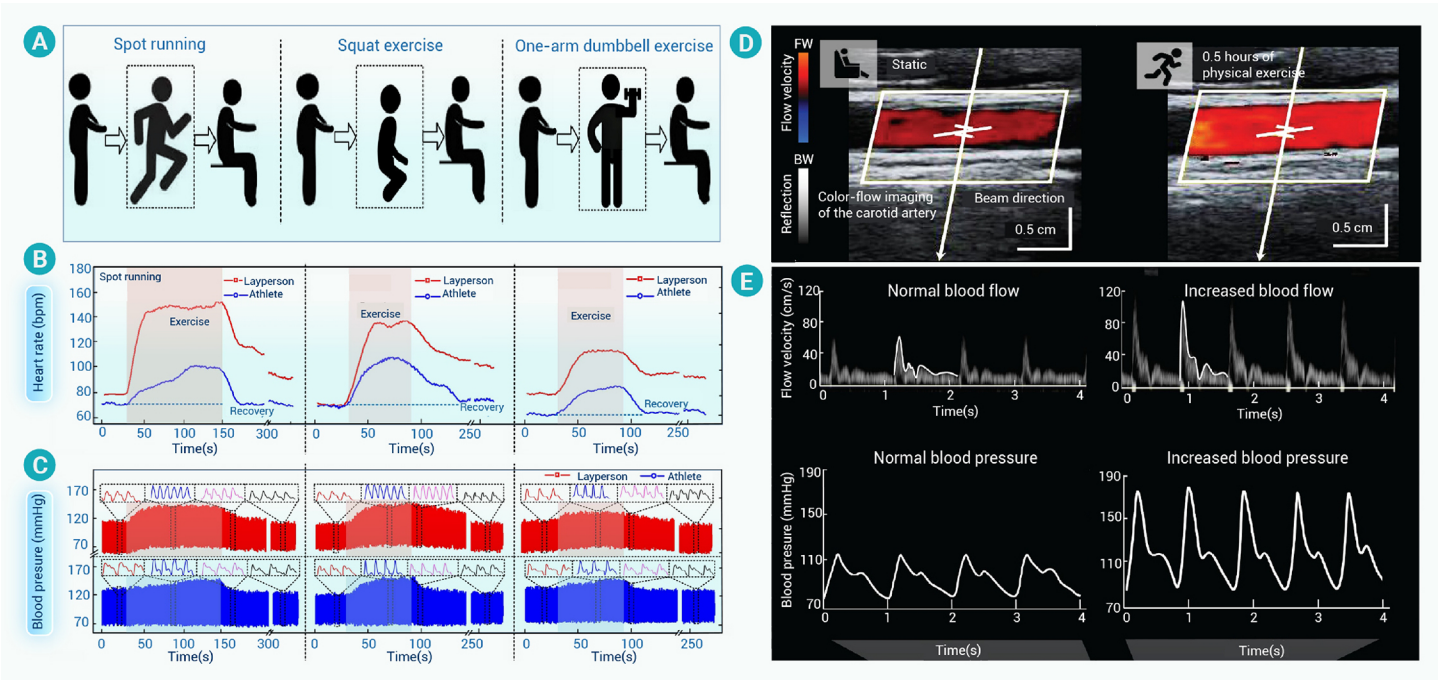

Figure 6. Continuous real-time monitoring of cardiac function during different phases of exercise (A) Schematic representation of various exercise modalities, including short-distance running, squats, and one-arm dumbbell exercises using a 2 kg weight. Modified appropriately and reproduced with permission.[30] Copyright 2025, American Association for the Advancement of Science. (B) The heart rate change graphs during short-distance running, squats, and one-arm dumbbell exercises. Modified appropriately and reproduced with permission.[30] Copyright 2025, American Association for the Advancement of Science. (C) The graphs showing the changes in blood pressure waveform changes during short-distance running, squats, and one-arm dumbbell exercises. Modified appropriately and reproduced with permission.[30] Copyright 2025, American Association for the Advancement of Science. (D) Color-flow imaging of the carotid artery by the BAUS device. The diameter of the carotid artery and the blood flow rate in the carotid artery increase substantially after 0.5 hours of physical exercise. F_w, forward; B_w, backward.Modified appropriately and reproduced with permission.[20] Copyright 2022, American Association for the Advancement of Science. (E) Blood pressure waveforms of the carotid artery before and after 0.5 hours of physical exercise. The systolic blood pressure of the carotid artery increases substantially after 0.5 hours of physical exercise. The decrease in the blood pressure from the systolic peak in each cardiac cycle is much steeper after 0.5 hours of physical exercise. Modified appropriately and reproduced with permission.[20] Copyright 2022, American Association for the Advancement of Science.

systolic function, diastolic function, and pulmonary congestion status, and dynamically reflect real-time fluctuations in cardiac function. This capability provides highly accurate data to support objective evaluation of therapeutic efficacy, individualized drug dose adjustment, and formulation of long-term management plans.[13] Compared with conventional monitoring methods, this technology enables assessment during natural physiological states, such as home rest or daily activities, yielding data that more accurately reflect real-world clinical conditions and effectively overcoming the limitations of hospital-based testing.

From a technological development and evolutionary perspective, early flexible ultrasound patch research prioritized continuous monitoring of core cardiac function indicators, addressing the inability of traditional techniques to dynamically track cardiac function changes. Subsequent integrated systems expanded monitoring boundaries, extending from isolated cardiac function assessment to evaluation of cardiopulmonary interactions in pathological states. This transition marked a transformative shift from quantitative cardiac function monitoring to comprehensive heart failure risk alerting across the disease course, substantially enhancing the comprehensiveness, accuracy, and clinical utility of early warning systems.[53] Currently, these studies collectively form a foundation for a future technical framework, though integration into a single validated system remains a key next step. With ongoing technological refinement and clinical translation, this approach is expected to further promote the transformation of heart failure monitoring toward home-based, long-term, and precision-oriented care, thereby providing crucial technical support for comprehensive management of chronic heart failure.[54]

Coronary heart disease. Coronary heart disease (CHD) is an ischemic cardiovascular disorder caused by atherosclerotic lesions in the coronary arteries, leading to narrowing or occlusion of the vascular lumen and subsequent myocardial ischemia, hypoxia, or necrosis. A central diagnostic challenge is the absence of typical symptoms at rest,[19] and conventional resting examinations therefore carry a high risk of underdiagnosis. Meanwhile, stress testing is limited in its ability to provide long-term dynamic monitoring. Flexible ultrasound patches, as wearable devices, enable continuous monitoring of cardiac structure, ventricular wall motion, and hemodynamic parameters during natural activities. They can capture subclinical manifestations of myocardial ischemia, offering a novel dimension for adjunctive CHD diagnosis and risk stratification. Emerging studies have confirmed their potential for clinical application.[10,30,51]

Clinical needs and limitations of traditional monitoring technologies. CHD has become a major global public health concern. According to national epidemiological survey data, the number of individuals with CHD in China has reached 11.39 million, with the age of onset showing a gradual downward trend. Early and precise monitoring, as a core component of secondary prevention for CHD, holds critical clinical significance for timely intervention in disease progression, improvement of patient prognosis, and reduction of mortality and disability rates.[51,55]

Within the clinical management pathway for CHD, core monitoring requirements encompass three key dimensions: dynamic quantitative assessment of the severity of coronary artery stenosis; early and precise identification of silent myocardial ischemia; and long-term follow-up monitoring of ischemic myocardial function. The integrated implementation of these three dimensions provides scientific and reliable evidence to support individualized optimization of clinical treatment strategies and objective evaluation of therapeutic efficacy, thereby enhancing the precision of CHD diagnosis and management.

Current clinical monitoring methods for CHD exhibit substantial limitations and fail to meet the demands for precise and long-term surveillance. Coronary angiography, the gold standard for CHD diagnosis,[56] is an invasive interventional procedure that carries inherent risks of procedural trauma and infection. Moreover, it provides only single time-point assessment and cannot support continuous long-term monitoring. Conventional transthoracic echocardiography relies on specialized operators and large ultrasound systems and is susceptible to interference from factors such as patient positioning, body habitus, and respiratory motion. Its results are partially operator-dependent, making detection of occult myocardial ischemia during routine

physiological states challenging.[57] Although ECG enables noninvasive monitoring of abnormalities in myocardial electrical activity, its sensitivity for detecting early myocardial ischemia is limited, and it cannot directly visualize structural cardiac lesions or quantify the severity of coronary atherosclerosis.[58] Existing wearable monitoring devices permit only preliminary tracking of basic vital signs, such as heart rate and blood pressure, and lack specific imaging and hemodynamic information related to coronary arteries and myocardial tissue. Consequently, they do not meet the clinical requirements for precise monitoring of CHD.[59]

Accordingly, the development of noninvasive, continuous, and wearable precision monitoring technologies for CHD has become a major research focus in cardiovascular biomedical engineering. Flexible ultrasound patches, leveraging their unique technical advantages, address many of the inherent limitations of traditional monitoring methods. They provide a promising technical solution to this clinical challenge and hold substantial potential for clinical translation and broad application in advancing CHD monitoring toward home-based, long-term, and precision-oriented models.

Breakthroughs in core technologies and clinical application progress. To address clinical challenges and technical bottlenecks in CHD monitoring, researchers have conducted systematic investigations into key technologies, including structural design, performance optimization, and signal processing of flexible ultrasound patches.[30] These efforts have yielded a series of core breakthroughs and progressively advanced the technology from fundamental laboratory research toward clinical pilot studies, thereby establishing multiscenario clinical application models.

At the core technology level, three principal breakthroughs have been achieved. First, optimization of the flexible substrate and transducer array has resulted in a lightweight patch measuring 2 × 4 cm and weighing approximately 2 g. This design incorporates a symmetrically arranged six-element transducer array and a pre-angled flexible substrate tilted at 30°.[60] Some studies have employed silicon CMUT arrays, which combine lead-free material composition with high transmission efficiency and low power consumption.[61] When paired with a self-adhesive hydrogel bonding layer, this configuration enhances skin conformity and signal stability, maintaining heart rate monitoring error within ± 2 beats per minute.[62] Second, multiparameter synchronous monitoring technology integrates Doppler ultrasound with speckle-tracking imaging modules. Blood flow velocity measurements maintain an error margin of 4.1%–12%, enabling quantification of myocardial strain and perfusion volume for comprehensive assessment of coronary artery disease lesions.[62] Third, signal denoising and intelligent algorithm integration incorporate adaptive noise-reduction algorithms to improve the ultrasound signal-to-noise ratio. When combined with machine learning–based automated anomaly detection, this approach is compatible with microelectromechanical systems manufacturing for scalable production. The per-patch cost is maintained below US$20, providing a practical foundation for clinical translation.[63]

Second, three principal clinical application scenarios have emerged. For early screening, the patch enables long-term home monitoring of high-risk populations, such as patients with hypertension and diabetes.[64] Yuan et al.'s patch effectively identifies silent myocardial ischemia at rest, whereas Peng Chang's team developed a stretchable patch capable of monitoring carotid hemodynamic parameters for early detection of coronary atherosclerosis. Emerging evidence suggests that flexible ultrasound patch technology has made promising advances in the assessment of coronary artery disease (CAD). The skin-conformal focused flexible ultrasound transducer developed by Yuan and colleagues demonstrated a measurement error of less than 25% in arterial stiffness assessment compared with reference devices in clinical evaluations.[30] Wang et al. further validated the device's ability to accurately measure blood flow velocity in deeply located arteries, yielding results consistent with those obtained using commercial ultrasound systems.[22] In addition, the silicon nanocolumn-based ultrasound patch developed by Kang and colleagues enabled continuous monitoring of carotid artery blood pressure waveforms, providing a novel approach for CAD risk assessment. [10] For longitudinal disease monitoring, myocardial strain measurements obtained using flexible ultrasound patches showed a strong correlation with those derived from conventional echocardiography ($r > 0.85$), highlighting their potential as a practical and less burdensome alternative for patient follow-up.[10] The silicon nanocolumn-based patch also enabled construction of personalized CHD risk prediction models based on extended continuous monitoring data, with its continuous dynamic tracking approach more effectively capturing intermittent ischemia and risk fluctuations, thereby providing important support for CHD risk stratification.[65] Collectively, these findings suggest that flexible ultrasound patches hold promise as adjunctive tools for early screening, disease follow-up, and long-term risk stratification of coronary artery disease. Nevertheless, their accuracy in the quantitative diagnosis of coronary artery stenosis requires further validation through large-scale prospective clinical studies.

These feasibility studies suggest the possibility of eventual clinical utility, but extensive clinical validation is required before this goal can be realized. However, they remain in the research and clinical pilot stages and have not yet achieved large-scale clinical implementation. Moreover, they continue to face multiple technical and clinical challenges. To address these limitations and align with the clinical demand for precise CHD monitoring, future research on flexible ultrasound patches should focus on core directions, including technical optimization and clinical translation. From a long-term developmental perspective, early-stage research has emphasized capturing key ischemia-related indicators under both resting and exercise conditions. Looking ahead to 2025 and beyond, efforts are expected to concentrate on two primary objectives: first, achieving extended continuous monitoring durations through higher-stability patch designs while constructing personalized risk prediction models; and second, enhancing quantification of stenosis severity by improving blood flow velocity measurement accuracy and refining parameter inversion strategies.

Cardiomyopathy. Cardiomyopathy is not a single disease entity but rather a group of highly heterogeneous disorders characterized by structural and functional abnormalities of the myocardium. Its pathophysiological progression typically follows a continuum, often originating at the microscopic or molecular level through events such as sarcomeric gene mutations, mitochondrial dysfunction, or autoimmune responses following viral infection. These processes lead to cardiomyocyte hypertrophy, apoptosis, interstitial fibrosis, and cytoskeletal remodeling, subsequently evolving into macroscopic cardiac structural abnormalities. Ultimately, the disease may progress to advanced heart failure accompanied by impaired tissue perfusion, fluid retention, and varying degrees of arrhythmic dysfunction.[66] Cardiomyopathies are generally categorized into hypertrophic, dilated, and restrictive types. These conditions are characterized by structural abnormalities and functional impairment of the myocardium, and early symptoms are often nonspecific, resulting in high rates of missed diagnosis and misdiagnosis. Distinct structural phenotypes differentiate the major subtypes. Hypertrophic cardiomyopathy is characterized by left ventricular hypertrophy, typically involving diffuse thickening of the interventricular septum and free wall; however, segmental hypertrophy may also occur, most commonly confined to the basal anterior septum or the apical region.[67] Dilated cardiomyopathy presents with left ventricular enlargement and global or regional systolic dysfunction.[68] Flexible ultrasound patches enable continuous acquisition of cardiac chamber dimensions, wall thickness, and wall motion data, thereby providing higher temporal resolution for early detection and longitudinal follow-up of these phenotypic changes.

Disease-related cardiac structure and data monitoring. With respect to structural parameter monitoring, existing research has established a core indicator framework for flexible ultrasound patches. In hypertrophic cardiomyopathy, the system can precisely measure interventricular septal thickness and left ventricular posterior wall thickness. Data from Chen S.'s team, based on a starfish-inspired wearable bioelectronic system, demonstrated measurement errors of only ± 0.2 mm for myocardial thickness, enabling accurate identification of the hallmark feature of hypertrophic cardiomyopathy, defined as septal thickness ≥ 15 mm. In dilated cardiomyopathy, the system effectively monitors parameters such as left ventricular end-diastolic diameter and end-systolic volume, capturing characteristic changes including chamber dilation and reduced contractility. Measurement of left ventricular end-diastolic diameter showed 91% concordance with conventional transthoracic echocardiography.[69]

The complexity of cardiomyopathy lies in the bidirectional interaction between structural abnormalities and electrical dysfunction. Fibrotic myocar-

dial regions may serve as substrates for reentrant excitation, thereby significantly increasing the risk of atrial fibrillation, nonsustained ventricular tachycardia, and sudden cardiac death.[70,71] Single-modality imaging provides limited comprehensive assessment, making multimodal signal fusion monitoring a critical strategy for enhancing diagnostic capability. Chen's team pioneered synchronous integration of flexible ultrasound patches with electrocardiographic monitoring technology. This integrated system simultaneously captures real-time cardiac anatomical data, such as wall motion and chamber dimensions, while recording high-fidelity ECG signals. This capability allows clinicians, during episodes of palpitations or syncope, not only to identify arrhythmias (e.g., ventricular premature beats and atrial fibrillation) but also to observe corresponding ventricular wall motion and chamber volume changes at the moment of the electrical event. Such synchronized assessment establishes a direct correlation among structural alterations, functional dynamics, and electrical activity. By quantifying the frequency of these events and correlating them with underlying myocardial structural abnormalities, this integrated monitoring approach achieved a diagnostic accuracy of 88% for cardiomyopathy with arrhythmia, representing a 23% improvement over single-modality ultrasound monitoring and significantly shortening the diagnostic process.[69] This multimodal signal fusion strategy uncovers additional diagnostic information and substantially enhances the precision and timeliness of early cardiomyopathy diagnosis.

Future development directions. From a technological perspective, this field has evolved along a trajectory from single structural monitoring to multiparameter integration and ultimately to multimodal signal fusion. Early investigations primarily focused on structural parameters directly measurable by ultrasound, such as myocardial thickness and cardiac chamber dimensions. With increasing device and algorithm maturity, research has incorporated functional indicators and electrophysiological information (e.g., ECG data), enabling synchronous analysis of structural, functional, and electrical parameters and thereby overcoming the limitations of traditional single-dimensional monitoring. If future validation in larger cardiomyopathy cohorts confirms the prognostic value of integrated indicators for predicting disease progression and sudden cardiac death risk[72]—particularly the predictive utility of combined markers, such as regional strain abnormalities coupled with specific ECG features, for long-term major adverse cardiovascular events (including heart failure hospitalization, malignant arrhythmia episodes, and sudden cardiac death)[73]—then this technology may move beyond its current role as an adjunctive diagnostic tool. If validated in larger cohorts, this integrated monitoring approach could evolve into a valuable adjunctive tool. Currently, it remains a research prototype. Under such circumstances, cardiovascular disease management may enter a new phase of precision medicine characterized by continuous monitoring, real-time alerts, and proactive intervention.

Postoperative follow-up and cardiac monitoring in cardiovascular surgery. Patients undergoing cardiac surgery require an extended recovery period, and monitoring for early postoperative complications as well as long-term functional follow-up is critical for prognostic assessment and therapeutic decision-making. Flexible ultrasound patches, characterized by their noninvasive and portable design and their capability for continuous imaging and quantitative measurement, can be applied in both in-hospital monitoring and home-based follow-up settings. For early postoperative complication monitoring, Wang C.'s team reported in 2022 that BAUS can continuously track cardiac function parameters (e.g., EF and SV) together with structural changes (e.g., pericardial effusion volume and cardiac chamber dimensions). This approach enables earlier detection of postoperative hemorrhage–related pericardial effusion compared with conventional bedside ultrasound and demonstrates high sensitivity for early warning of acute postoperative heart failure.[20] In special populations, a 2025 neonatal case study by Wang Y.'s team demonstrated that flexible ultrasound patches enabled 72-hour continuous monitoring, capturing transient arrhythmias and fluctuations in cardiac function, thereby providing a feasible solution for refined postoperative management in newborns.[74] For long-term follow-up and home rehabilitation monitoring, Wang C.'s team further demonstrated that the device achieved axial and lateral spatial positioning accuracies of 96.01% and 95.90%, respectively, with a dynamic range of 63.2 dB. No significant performance differences were observed compared with conventional commercial ultrasound systems. This technological advancement establishes a hardware foundation for remote cardiac function assessment during postoperative home rehabilitation. The field is currently accelerating its transition from technical validation to clinical translation. In 2023, Mohamed et al. reported a tablet-integrated wearable patch sensor system employing a rigid–flex printed circuit board design to enhance lightweight wearability. The system integrates auscultation of heart and lung sounds with short-range ECG signal acquisition and applies adaptive noise-cancellation algorithms to improve signal quality. This approach provides a system-level solution for real-time multimodal cardiovascular parameter monitoring.[75]

From the perspective of technological evolution, flexible ultrasound patches are progressively moving beyond their initial limitation to short-term in-hospital monitoring. They are advancing toward home-based long-term follow-up, multimodal parameter fusion, and artificial intelligence (AI)–assisted diagnosis. In the future, through integration of remote data transmission with real-time AI analysis, this technology may enable precise tracking of postoperative cardiac recovery trajectories, automated identification of early warning indicators, and dynamic adjustment of personalized rehabilitation plans. Ultimately, this approach may facilitate the establishment of a closed-loop management system encompassing in-hospital precision monitoring, home-based remote follow-up, and intelligent anomaly alerting. Such a paradigm shift has the potential to improve long-term prognostic outcomes for cardiac surgery patients, while optimizing healthcare resource allocation, reducing readmission rates, and alleviating societal healthcare burdens.

In summary, the application of flexible ultrasound patches in monitoring different cardiovascular diseases is essentially a mapping process from general imaging and measurement capabilities to disease-specific engineering metrics. Heart failure demands deep penetration (> 4 cm) and long-term stability (≥ 48 h); coronary heart disease requires high frame rate (≥ 50 fps) and motion artifact resistance; cardiomyopathy depends on high spatial resolution (< 0.5 mm) together with electromechanical synchronous acquisition; postoperative follow-up emphasizes wireless transmission, low power consumption (< 100 mW), and user-friendliness. Current research is mostly focused on feasibility validation in single disease scenarios, and there remains a lack of systematic device optimization and cross-disease comparative studies addressing these specific requirements.

For clarity and comparative purposes, Table 4 systematically summarizes the key applications and challenges of flexible ultrasound patches in the context of cardiovascular diseases, including the application areas, monitoring metrics, representative technical methods, technology maturity, core value and application scenarios, as well as the key challenges and constraints.

FUTURE DEVELOPMENT DIRECTIONS AND CHALLENGES

Technical and clinical challenges

As demonstrated in the preceding sections, flexible ultrasound patches possess distinct advantages, including noninvasiveness, portability, and the capacity for continuous monitoring, and they show considerable potential in cardiovascular function assessment and disease management. However, to transition from laboratory prototypes to routine clinical implementation, several technical and clinical issues that are highly relevant to cardiovascular applications must be systematically addressed. These challenges encompass not only engineering constraints, such as limited imaging resolution and motion artifacts, but also translational barriers, including standardization of measurement protocols, alignment with gold-standard reference methods, and the establishment of robust clinical evidence systems.[76,77]

Spatial resolution and motion artifacts. First, spatial resolution (SR) determines the upper limit for identifying fine cardiac structures and accurately measuring related parameters. However, the SR limitations encountered by flexible ultrasound patches in cardiac monitoring are highly scenario-specific. Constrained by the mechanical properties of the flexible substrate and the miniaturized transducer array, their SR is generally inferior to that of conventional desktop ultrasound systems.[53] The principal limitation lies in the visualization of fine myocardial structures. These devices cannot clearly delineate subtle anatomical features such as myocardial trabeculae and endocardial borders and therefore struggle to meet the requirements for

precise identification of early myocardial lesions (e.g., mild myocardial hypertrophy and focal myocardial ischemia). Consequently, relatively large measurement errors may occur in key parameters, including ventricular volume and EF, which constitutes one of the primary reasons for discrepancies compared with gold-standard modalities such as cardiac magnetic resonance (CMR) imaging.[78]

Second, motion artifacts in cardiac monitoring arise from multiple superimposed sources and are closely coupled with the intrinsic motion pattern of cardiac pulsation, making them difficult to mitigate using existing technologies. On the one hand, the periodic, high-frequency contraction and relaxation of the heart (heart rate, 60–100 beats per minute) induce synchronous micromovements between the patch and the skin. Even with optimal adhesion, such dynamic displacement cannot be completely eliminated, resulting in image blurring and endocardial border distortion. On the other hand, respiratory motion, body movement, and cardiac pulsation collectively generate multisource interference. When combined with mechanical deformation of the flexible patch itself, these factors further exacerbate signal displacement and significantly degrade the dynamic tracking accuracy of hemodynamic parameters such as SV and CO.[79]

Particularly challenging is the subtle yet persistent chest wall motion induced by cardiac pulsation, which may result in patch edge lifting, uneven contact pressure, and localized failure of the coupling layer during long-term wear. This phenomenon not only increases motion artifacts but also leads to echo attenuation and, in some cases, data interruption. The issue is especially pronounced during long-term bedside monitoring and exercise stress testing, thereby necessitating coordinated optimization of coupling materials, fixation strategies, and artifact suppression algorithms.

Challenges in clinical translation. Clinical translation of flexible ultrasound patches faces multiple barriers, most of which are directly associated with the high-precision and high-safety requirements of cardiac monitoring. Consequently, their translation is substantially more complex than that of conventional wearable devices. Among these challenges, issues related to technical standardization are particularly prominent. The field currently lacks dedicated specifications tailored to cardiac monitoring scenarios that adequately account for their unique physiological and clinical characteristics. There is no unified standard for transducer array design (e.g., array configuration aligned with cardiac anatomy), imaging parameter calibration procedures (e.g., parameter adjustment for different heart rates and cardiac functional states), or data acquisition protocols.[80] Existing standards largely follow the frameworks established for traditional ultrasound systems or general wearable devices, resulting in limited comparability of cardiac monitoring results across different products. This limitation hampers the establishment of unified clinical evaluation criteria and fails to satisfy the consistency requirements necessary for clinical diagnosis.[81]

At present, the clinical translation and industrialization of flexible ultrasound patches are still restricted by the lack of unified technical specifications. It is urgent to establish consistent evaluation systems, including standardized transducer performance parameters, unified in vitro simulation test protocols, certified artificial skin phantom models, and long-term wear stability assessment criteria. Establishing these unified norms will help standardize experimental data, improve repeatability, and accelerate the clinical implementation and large-scale commercialization of flexible ultrasound patches.

With respect to data validity, existing studies exhibit clear scenario-specific limitations and insufficient alignment with the clinical demands of cardiac disease management. Most investigations are based on small cohorts of healthy subjects or simulated cardiac motion conditions, lacking large-sample, multicenter clinical data involving patients with heart failure, CHD, and other high-risk or elderly populations.[1] In addition, cardiac monitoring frequently requires continuous wear exceeding 72 hours. Prolonged skin contact may induce irritant contact dermatitis, and mechanical deformation of the patch may introduce measurement bias. Available safety and efficacy data remain limited, and the consistency of parameter measurements with gold-standard modalities such as CMR imaging requires further validation.[82]

In addition, regulatory approval for medical devices is highly stringent. As a novel cardiac diagnostic technology, flexible ultrasound patches must comply with full life-cycle risk management requirements. At present, no dedicated evaluation framework exists for cardiac monitoring applications of this technology. Their performance in identifying fine cardiac structures and maintaining parameter stability under exercise stress cannot be adequately assessed using existing evaluation criteria. This limitation leads to prolonged clinical evidence generation cycles and increased costs, further delaying translational progress and hindering rapid implementation in frontline clinical practice.

Prospects for the expansion of clinical applications. Despite the substantial challenges described above, the clinical potential of flexible ultrasound patches remains evident. Their value does not lie in replacing all conventional desktop ultrasound examinations, but rather in providing continuous, scenario-specific, and quantifiable information that traditional modalities cannot readily obtain. Future development should be guided by clearly defined clinical needs, emphasizing targeted technological innovation and application-oriented solutions to address the aforementioned limitations. This approach will facilitate their evolution from auxiliary monitoring tools to platforms supporting precise diagnosis and comprehensive disease lifecycle management, thereby complementing existing examination methods and contributing to an integrated cardiovascular management system encompassing prevention, diagnosis, treatment, and rehabilitation.[83]

To address the limitation in SR for detecting subtle myocardial structures, efforts should focus on improving element density and effective aperture at the transducer array level (e.g., through higher-frequency elements, two-dimensional arrays, and multiplexed interconnections) and optimizing flexible substrates to minimize deformation-induced imaging degradation. In parallel, deep learning–based image enhancement and boundary segmentation algorithms should be integrated to improve measurement stability for parameters such as endocardial contour definition and ventricular wall thickness, thereby progressively narrowing the performance gap with gold-standard modalities such as CMR imaging.

To mitigate insufficient fitting stability and multisource motion artifact interference, coordinated optimization is required across three domains: structural fixation, material coupling, and algorithmic correction. Personalized patch designs and adjustable fixation mechanisms tailored to individual chest wall anatomy should be developed, and highly adhesive, low-irritation, and dehydration-resistant coupling materials should be employed to reduce micromotion. Simultaneously, ECG–synchronized triggering or phase-gating strategies should be introduced to align cardiac cycles and distinguish physiological cardiac motion from respiratory and body movement interference. When combined with dedicated artifact suppression algorithms, these strategies may improve beat-to-beat tracking accuracy of hemodynamic parameters under exercise load.[84]

To address the lack of standardization and insufficient clinical data, collaboration among medical institutions, industry partners, and research teams is essential to promote the development of patch design specifications, standardized parameter calibration procedures, and data collection and quality control standards tailored to continuous cardiac monitoring applications. In parallel, large-sample, multicenter clinical studies involving key CVDs and special populations should be conducted to systematically verify the consistency of critical parameters with gold-standard modalities and to strengthen evidence regarding long-term wear safety. On this basis, an evaluation framework suitable for regulatory review should be established to facilitate a shortened translational timeline.[85]

With respect to the expansion of specific application scenarios, precise alignment with differentiated clinical needs is required. Home-based management prioritizes low power consumption, user-friendly operation, and reliable remote data transmission, integrated with early warning mechanisms to support long-term follow-up of patients with heart failure. Exercise rehabilitation settings require optimization of motion artifact suppression algorithms and real-time parameter feedback to guide rehabilitation plan adjustments following myocardial infarction. Emergency and prehospital care scenarios necessitate enhanced rapid deployment and real-time analytical capabilities to assist in timely triage of acute chest pain. For pediatric patients with congenital heart disease, further miniaturization and increased flexibility of patch designs are needed to accommodate pediatric chest wall characteristics and to reduce discomfort during prolonged wear.

Table 4. The application and challenges of flexible ultrasound patches in cardiovascular diseases.

Application Area	Monitoring Metrics	Representative Technical Methods	Core Value & Application Scenario	Key Challenges & Constraints	Refs
Coronary Artery Disease	Myocardial Perfusion; Regional Wall Motion Abnormality (RWMA); Coronary Flow Velocity; Ischemia Index	Contrast-Enhanced Wearable Ultrasound; Speckle-Tracking Imaging (STI); Color Doppler Imaging	Early silent ischemia diagnosis; Exercise stress monitoring; Post-PCI functional assessment	Low spatial resolution; Motion-induced artifacts; Limited chest penetration; Contrast agent optimization	63,64,71,72
Arrhythmia	Ventricular Wall Synchrony; Atrial Mechanical Function; Valve Movement; Cardiac Cycle Variability	M-Mode Wearable Ultrasound; Tissue Doppler Imaging (TDI); High-Frame-Rate Imaging	Paroxysmal AF screening; Ventricular dyssynchrony evaluation; Post-ablation follow-up	Low temporal resolution; Signal crosstalk; Atrial imaging difficulty; Power consumption constraints	68,73,74
Valvular Heart Disease	Valve Leaflet Motion; Regurgitant Jet Velocity; Valve Area; Transvalvular Pressure Gradient	Continuous/Pulsed Wave Doppler; 2D/3D Wearable Echocardiography; Flow Visualization	Chronic valvulopathy monitoring; Post-valve replacement follow-up; Home-based severity assessment	Complex flow quantification; Low-velocity signal loss; Chest wall interference; Calibration difficulty	68,73,74

Future development directions

To achieve the transition from laboratory innovation to routine clinical implementation, the future development of flexible ultrasound patches may be summarized into two parallel and complementary directions. The first involves innovation in materials and manufacturing processes, aiming to establish a more stable and scalable hardware platform capable of ensuring acoustic performance and long-term wear reliability. The second focuses on intelligent algorithm development and system integration to enable more efficient beamforming, motion artifact suppression, and parameter extraction at the edge-computing level, while facilitating seamless integration with wireless communication systems and clinical workflows.

It should be emphasized that materials, manufacturing processes, and algorithms are not independent components. Improvements in hardware performance can reduce reliance on algorithmic compensation, whereas advances in algorithms may, in turn, expand hardware design flexibility. Together, these elements form a coordinated closed-loop framework in which hardware capabilities enhance software performance, and software optimization informs hardware refinement.[85]

Different types of flexible ultrasound patches have their own inherent advantages and limitations. Piezoelectric array patches feature high imaging resolution but suffer from motion artifacts and poor stretchability; CMUT-based patches provide good flexibility and biocompatibility yet are limited in imaging penetration depth. Meanwhile, practical challenges including skin irritation, signal stability and lack of unified evaluation standards still restrict their large-scale clinical promotion.

Optimization of high-precision and low-cost manufacturing processes. In the field of materials and manufacturing processes, the primary development objective is to establish a clinical-grade flexible ultrasound patch system characterized by high sensitivity, low cost, and extended service life. Achieving this objective requires material innovation as a fundamental prerequisite and provides stable and reliable hardware support for subsequent optimization of intelligent algorithms.

At present, research efforts are directed toward the development of a new generation of high-performance flexible functional materials. Although traditional piezoelectric ceramics (e.g., lead zirconate titanate) exhibit excellent piezoelectric properties, their intrinsic brittleness substantially limits their conformability to dynamic skin surfaces. In contrast, currently mainstream flexible piezoelectric polymers (e.g., polyvinylidene fluoride) face the prominent limitation of insufficient piezoelectric response magnitude. This material-level constraint not only restricts manufacturing process compatibility but also increases the demand for subsequent algorithmic signal compensation.[86]

To address these challenges, nanocomposite strategies have emerged as a key approach for enhancing flexible piezoelectric materials. By incorporating inorganic fillers such as barium titanate ($BaTiO_3$) and zinc oxide (ZnO) into polymer matrices, electromechanical conversion efficiency can be synergistically improved while preserving material flexibility.[87,88] Such modification strategies not only enhance mechanical flexibility and piezoelectric responsiveness but also create favorable conditions for scalable and cost-effective manufacturing.[89,90]

Complementing material innovation is the advancement of high-precision, low-cost, and scalable fabrication technologies. Conventional microfabrication processes are often insufficient for producing large-area flexible substrates, whereas printed electronics techniques (e.g., inkjet printing and roll-to-roll manufacturing) and emerging methods such as pressure-constrained sonic activation offer viable solutions for mass production of high-density ultrasound transducer arrays. Process-level optimization not only reduces systematic hardware fabrication errors but also alleviates the burden of algorithmic signal compensation, thereby promoting coordinated development between manufacturing processes and intelligent algorithms.

Improvement of long-term material stability and durability. In addition to manufacturing cost, long-term stability and durability represent critical determinants for clinical application. Material aging, encapsulation fatigue, or degradation of the coupling layer may lead to signal drift, thereby compromising parameter extraction accuracy and increasing reliance on algorithmic compensation. Consequently, current research advances along two complementary dimensions: optimization of encapsulation strategies and intrinsic modification of material properties, with the aim of maintaining stable performance during prolonged wear.

For example, the application of self-healing polymer encapsulation technologies can effectively mitigate mechanical damage to flexible patches during extended use.[91] Similarly, the incorporation of liquid metal electrodes can substantially enhance interfacial stability under repeated mechanical deformation.[92] These material and encapsulation optimization strategies reduce signal fluctuations induced by skin deformation and long-term wear, decrease the burden of motion artifact compensation algorithms, and indirectly improve the accuracy and robustness of parameter extraction. Furthermore, ordered microporous materials have been shown to enhance mechanical stability and thermal management in polymer-based composites, which may inspire the design of durable and acoustically efficient coupling layers for flexible ultrasound patches.[93]

Multidisciplinary technology integration and in-depth optimization of intelligent algorithms. At the level of intelligent assistance, advanced algorithms constitute a critical foundation for addressing core challenges in imaging and monitoring with flexible ultrasound patches and serve as a pivotal link between material innovation and process enhancement. Improvements in material properties and manufacturing precision provide clearer and more stable raw monitoring signals for algorithmic processing; conversely, algorithmic optimization can maximize hardware performance and partially compensate for limitations that remain unresolved at the material and fabrication levels.

To address the persistent challenge of motion artifacts in flexible ultrasound monitoring, signal processing strategies based on physical modeling or data-driven approaches have been widely implemented. These methods enable compensation for signal distortions induced by respiratory motion, body movement, and other sources of interference. Such algorithmic strate-

gies are well suited to dynamic skin-surface applications and function synergistically with material flexibility and encapsulation stability to maintain the accuracy of dynamic monitoring. Beyond these algorithmic strategies, the integration of machine learning and brain-inspired artificial synapses into flexible sensing systems has enabled intelligent data analysis, multimodal decoupling, and even artificial sensory perception, which holds great promise for advancing flexible ultrasound patches toward autonomous and adaptive cardiovascular monitoring.[94]

With respect to core parameter extraction, training robust computational models using multicenter datasets and heterogeneous population samples can substantially improve the consistency and accuracy of measurements for key clinical indicators, including SV, CO, and EF, while reducing reliance on operator experience. This algorithm optimization strategy can also accommodate hardware variability arising from large-scale manufacturing, thereby enabling coordinated adaptation between batch production processes and precision algorithm deployment.

In the future, algorithm optimization should further address challenges such as limited generalizability under small-sample conditions and low real-time computational efficiency on resource-constrained wearable devices, thereby ensuring technological reliability and practical applicability in real-world clinical settings. This optimization pathway must be closely aligned with advancements in materials and manufacturing processes, adapting to increasingly thinner and stretchable structural designs while remaining compatible with hardware characteristics associated with low-cost, large-scale production. Ultimately, such efforts will facilitate coordinated integration among materials, processes, and algorithms.

Looking ahead, with the establishment of a more comprehensive standardization framework and robust large-sample clinical evidence, flexible ultrasound patches are expected to reshape clinical workflows in scenarios including home-based management of high-risk populations, perioperative monitoring, exercise rehabilitation, and telemedicine. They will provide continuous and quantifiable objective evidence to support early screening, early diagnosis, and long-term management of CVDs.

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DECLARATION OF INTERESTS

The authors declare no competing interests.

DATA AND CODE AVAILABILITY

No new data and code were created or analyzed in this review.