REVIEW ARTICLE

Wearable Ultrasound in Cardiovascular Monitoring: Clinical Evidence and Translational Challenges

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Objective: Wearable ultrasound is emerging as a promising approach for continuous cardiovascular monitoring, extending conventional ultrasound from intermittent examinations to prolonged, hands-free assessment. This review summarizes recent progress in these major cardiovascular applications, with particular attention to their clinical validation and translational potential.

Methods: A literature search was performed using PubMed (January 2021 to August 2026) utilizing keywords related to wearable ultrasound (e.g., "wearable", "skin-mounted", "ultrasound", "Doppler") combined with cardiovascular terms. Eligible original research articles, including human studies, animal investigations, and ultrasound sensing-platform studies that demonstrated relevant mechanisms or technical feasibility, were selected.

Results: Recent advances in flexible transducers, stable acoustic coupling, and automated signal analysis have enabled continuous cardiac imaging, non-invasive blood pressure monitoring, and dynamic assessment of vascular hemodynamics and arterial stiffness. Current studies have demonstrated continuous acquisition of cardiac images and functional parameters, cuffless blood pressure tracking under dynamic conditions, and wearable measurement of vascular flow and local arterial mechanical properties. Among these applications, continuous cuffless blood pressure monitoring currently has the most mature clinical validation. However, most applications remain at the physiological validation or early clinical feasibility stage, and evidence for long-term reliability, generalizability, and clinical benefit is still limited.

Conclusion: Future research should focus on robust continuous monitoring in real-world patients and on demonstrating whether wearable ultrasound can provide clinically actionable information beyond conventional intermittent ultrasound.

Key words: Wearable ultrasound; Flexible ultrasonic transducer; Cuffless blood pressure; Continuous hemodynamic monitoring; Cardiovascular monitoring

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Cardiovascular disease remains a leading cause of death and disability worldwide. Global Burden of Disease data show that it continues to account for a substantial proportion of global mortality and disability-adjusted life years [1]. Cardiovascular physiology is inherently dynamic: cardiac function, blood pressure, blood flow, and vascular wall mechanics vary with posture, exercise, emotional stress, treatment, and disease progression. Continuous, non-invasive assessment of cardiovascular structure and hemodynamics therefore addresses an important limitation of intermittent examinations.

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Wearable sensing technologies based on electrocardiography (ECG) and photoplethysmography (PPG) have enabled long-term out-of-hospital recording of heart rate, rhythm, and peripheral pulse signals. However, these modalities primarily capture electrical activity or superficial optical volume changes and do not directly characterize ventricular motion, deep-vessel dimensions, blood-flow velocity, or vascular wall mechanics [2]. Cuff-based blood pressure measurement is intermittent, whereas invasive arterial pressure monitoring provides beat-to-beat data but requires arterial catheterization and is therefore largely confined to perioperative and intensive care unit (ICU) settings because of infection, bleeding, and vascular complications [3,4]. Conventional echocardiography and vascular ultrasound provide rich structural and flow information, but their dependence on bulky equipment, trained operators, and episodic examinations limits prolonged monitoring [5].

Wearable ultrasound offers a potential bridge across this gap. Advances in flexible piezoelectric materials, micromachining, system integration, and artificial intelligence (AI) have enabled a transition from conventional handheld probes to conformal, skin-mounted platforms [6-8]. In cardiovascular applications, wearable ultrasound has enabled continuous cardiac imaging with automated left ventricular analysis [9], continuous blood-pressure monitoring and carotid flow assessment [10-12], transcranial three-dimensional Doppler imaging [13], and AI-assisted identification of elevated central venous pressure in critically ill patients [14].

This review focuses on the clinical translation of wearable ultrasound for cardiovascular monitoring. We first summarize the enabling technologies, then examine continuous cardiac-function assessment, non-invasive blood-pressure monitoring, vascular hemodynamics and arterial stiffness, and emerging applications. Particular emphasis is placed on the maturity of clinical evidence, reference-standard validation, and the barriers that must be addressed before routine use.

For this review, wearable ultrasound is operationally defined as an ultrasound sensing or stimulation platform designed to remain attached to the body and permit repeated or continuous acquisition or stimulation without an operator continuously holding the transducer. Wearability does not require a flexible transducer, wireless communication, or fully integrated processing; wired patches connected to external acquisition systems are therefore included. Conventional handheld ultrasound examinations, non-ultrasound wearable sensors, and fully implanted ultrasound devices are outside the primary scope.

The literature search was performed using PubMed, covering the period from January 2021 to August 2026. The keywords used for the research were “wearable”, “skin-mounted”, “ultrasound”, “ultrasonic”, “Doppler”, combined with cardiovascular terms including “cardiovascular”, “cardiac”, “heart”, “blood pressure”, “blood flow”, “hemodynamic”, “haemodynamic”, “arterial”, “artery”, “arteries”, “vascular”, and “venous”. Eligible original research included human studies, animal investigations, and ultrasound sensing-platform studies. Human studies included healthy-volunteer investigations, patient cohorts, case series, and individual case reports. Animal studies and bench or phantom evaluations of ultrasound sensing platforms were considered when they demonstrated relevant mechanisms, technical feasibility, or enabling technologies. Studies were excluded when the wearable component used a non-ultrasound sensing modality, ultrasound served only as a reference examination, the device was fully implanted, or the application fell outside the review scope. Of 170 retrieved records, 40 relevant original research articles were selected according to the inclusion criteria and exclusion criteria.

Technological Foundations of Wearable Ultrasound

Wearable ultrasound is not simply a miniaturized conventional probe. Clinically useful systems must acquire stable and interpretable signals over time with minimal operator intervention. Three elements are central: conformal transducers and system integration, durable acoustic coupling, and automated tracking and parameter extraction [6,7,15]. Figure 1 illustrates the overall workflow from ultrasound signal acquisition through on-board processing and wireless transmission to automated analysis and cardiovascular parameter output.

Conformal transducers and system integration

Conventional rigid probes are poorly suited to prolonged attachment over curved surfaces such as the chest, neck, and limbs. Flexible piezoelectric arrays, micromachined ultrasonic transducers, and stretchable interconnects can better conform to body contours while maintaining acoustic contact during motion [15-17]. Hu et al. developed a chest-mounted cardiac imager capable of continuous cardiac imaging [9], whereas Lin et al. integrated a flexible transducer, control electronics, and wireless communication into a single platform for autonomous monitoring of deep tissues during movement [5].

For clinical use, flexibility or piezoelectric performance alone is insufficient. A wearable transducer must preserve penetration depth, signal quality, and target

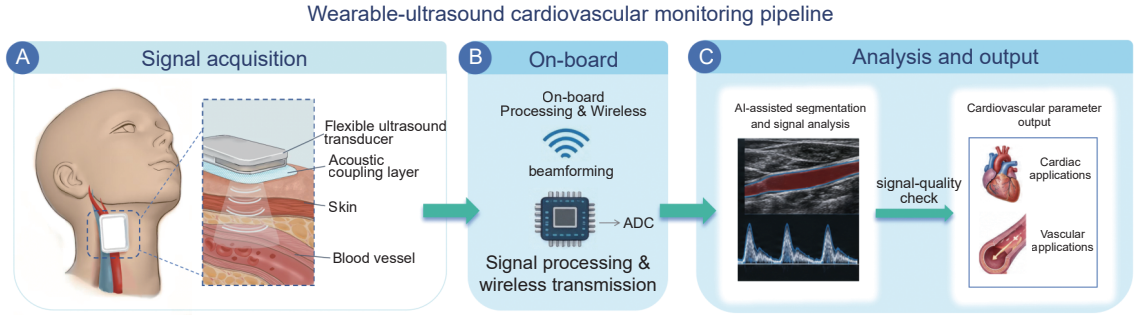


Figure 1 Conceptual pipeline for wearable ultrasound cardiovascular monitoring. (A) Signal acquisition using a flexible ultrasound transducer and an acoustic coupling layer at the skin interface; (B) On-board electronics support signal acquisition, processing, and wireless transmission; (C) AI-assisted segmentation and signal analysis, together with signal-quality assessment, enable parameter extraction for cardiac and vascular applications. The schematic illustrates a general workflow; the implementation and location of processing steps vary across devices. ADC, analog-to-digital converter; AI, artificial intelligence.

coverage across different body contours and activity states. Accordingly, the field is shifting from device flexibility alone toward long-term signal stability and higher levels of system integration.

Long-term acoustic coupling and motion stability

A stable skin-transducer interface is essential for continuous monitoring. Conventional liquid coupling agents can dry out or migrate during prolonged use. Wang et al. developed a bioadhesive ultrasound patch using a hydrogel-elastomer coupling layer that maintained skin contact and supported continuous imaging for up to 48 h in human testing [18].

Signal stability nevertheless remains vulnerable to perspiration, respiration, postural change, muscle motion, and relative patch displacement. In cardiac and vascular applications, small positional shifts may move the target outside the effective acoustic window. Future systems therefore need not only more robust fixation and coupling, but also automated detection of target loss, dynamic compensation, and signal-quality control.

Automated tracking and extraction of clinical parameters

Conventional ultrasound relies on real-time operator adjustment to obtain and maintain appropriate views. Truly continuous wearable monitoring requires this dependence to be reduced. Automated target tracking, image segmentation, and physiological parameter extraction are therefore core components of wearable systems.

For cardiac monitoring, deep-learning algorithms can segment the left ventricle (LV) from continuous images, generate volume-time curves, and derive stroke volume (SV), cardiac output (CO), and left ventricular ejection fraction (LVEF) [9]. For vascular monitoring, automated wall and lumen tracking can provide vessel diameter, blood pressure, and local mechanical indices, while Doppler signals yield flow velocity and timing parameters. Lin et al. further used machine learning to track moving deep-tissue targets with minimal operator input [5].

The key transition is therefore from a skin-mounted probe to an integrated monitoring pipeline comprising stable acquisition, automated tracking, quality control, and parameter extraction (Fig. 1). The clinical value of prolonged monitoring depends on whether continuous images and signals can be converted reliably into interpretable quantitative information.

Continuous Monitoring of Cardiac Function

Continuous cardiac imaging and quantification of systolic function

Continuous non-invasive cardiac assessment is one of the most distinctive applications of wearable ultrasound. Conventional echocardiography provides detailed structural and functional information but remains episodic and operator dependent. Wearable patches offer a potential route to hands-free monitoring at the bedside, at home, and during physical activity [9].

In 2023, Hu et al. reported a wearable cardiac ultrasound imager capable of continuous real-time B-mode imaging in humans [9]. Two orthogonal arrays allowed acquisition of commonly used echocardiographic views, including apical four-chamber, apical two-chamber, parasternal long-axis, and parasternal short-axis views without manual probe rotation. The 3-MHz transducer used a 0.4-mm element pitch to balance penetration and spatial resolution. Deep-learning segmentation of the LV generated continuous volume-time curves from which end-diastolic volume (EDV), end-systolic volume (ESV), SV, CO, and LVEF could be derived. LV volumes and derived functional indices showed good agreement with commercial echocardiography in the evaluated cardiac cycles [9]. The major advance was therefore not continuous image acquisition alone, but conversion

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of continuous imaging into quantitative cardiac-function trajectories.

Lin et al. extended this concept with a fully integrated ultrasonic-system-on-patch (USoP) for autonomous monitoring of deep tissues in moving subjects. The system tracked physiological signals from depths of up to 164 mm and monitored central blood pressure, heart rate, and CO for up to 12 h during movement [5]. Although the system was not designed primarily for direct cardiac imaging, it demonstrated that wearable ultrasound can support prolonged autonomous cardiovascular monitoring with limited operator intervention.

A subsequent dual-patch system enabled synchronous cardiac and carotid ultrasound monitoring, combining automated image analysis with a circulatory model. Evaluation in five healthy participants and three patients with coronary and/or carotid artery disease demonstrated early feasibility for integrated cardiovascular assessment, but the very small patient sample does not establish diagnostic performance [19].

Key parameters and validation characteristics of these and other cardiac monitoring studies are compared in table 1. These findings should nevertheless be interpreted cautiously. The study by Hu et al. primarily established proof-of-concept and physiological validation in healthy participants and evaluated a limited number of cardiac cycles rather than diagnostic performance in patients with heart failure, cardiomyopathy, or perioperative instability[9]. Wearable images also differ systematically from conventional echocardiography in view angle, resolution, and acoustic-window stability. Most current segmentation models have been trained under controlled conditions. A self-supervised segmentation pipeline trained on 450 conventional echocardiographic examinations and tested on 18,423 examinations achieved performance comparable to supervised approaches [20], and fine-tuned foundation models have shown improved cross-device and cross-institution generalization [21]. However, these approaches still require dedicated validation on wearable cardiac ultrasound. At present, wearable ultrasound has demonstrated the ability to acquire images suitable for quantitative LV systolic assessment, but its clinical performance across diverse cardiovascular diseases remains unestablished.

Cardiac monitoring during exercise and dynamic physiological states

The main advantage of wearable ultrasound over repeated resting examinations may lie in continuous monitoring under dynamic conditions. Conventional stress echocardiography generally acquires images before exercise, immediately after exercise, or at selected stages; maintaining a stable cardiac view throughout active exercise is difficult.

Hu et al. continuously recorded LV motion at rest, during cycling, and throughout recovery [9]. B-mode and M-mode signals remained obtainable despite marked increases in heart rate. During recovery, automated analysis captured continuous changes in LV volume, SV, CO, LVEF, and heart rate. Such trajectories provide physiological information that cannot be reconstructed reliably from a few isolated measurements.

Exercise monitoring remains constrained by cardiac acoustic-window availability. In the Hu study, LV dimensions were not consistently measurable in the standing position, and deep inspiration after strenuous exercise could transiently obscure the cardiac acoustic window with lung tissue [9]. Continuous detection of cardiac activity is therefore not equivalent to continuous quantitative echocardiography.

Continuous monitoring of heart rate and mechanical cardiac activity

In addition to B-mode imaging, M-mode ultrasound can provide high-temporal-resolution tracking of cyclic myocardial motion and can be used to derive heart rate. Unlike ECG, which records electrical activity, M-mode ultrasound directly reflects mechanical contraction. This distinction may be useful in settings such as pulseless electrical activity (PEA), where organized electrical activity may persist without effective mechanical contraction[6]. However, ECG remains substantially better established for long-term arrhythmia detection. The more distinctive role of wearable ultrasound may be complementary mechanical assessment. When integrated with ECG and PPG, it can align electrical activation, pulse transmission, and cardiac mechanical contraction within a single continuous recording.

Myocardial strain and diastolic function

Myocardial strain is a sensitive marker of systolic and diastolic function and is conventionally assessed using speckle tracking or tissue Doppler imaging (TDI). Translation to wearable ultrasound is technically challenging because deformation of flexible arrays changes element geometry and can introduce beamforming errors. Huang et al. highlighted the need for phase correction and shape-estimation algorithms to compensate for geometric distortion [15]. Adaptive beamforming with geometry-aware phase correction may therefore provide a signal-processing basis for future wearable strain analysis.

Clinical evidence for diastolic-function assessment remains limited. Continuous LV volume curves from the Hu platform captured filling dynamics, but wearable measurements of standard indices such as E/A or e' have

Table 1 Representative studies of wearable ultrasound for continuous cardiac function monitoring

Author/year	Population	Device/mode	Integration level	Freq./depth	Cardiac target	Monitoring	Comparator	Key findings	Limitation/ evidence stage
Wang/2021[17]	Healthy volunteers	Stretchable US phased array (Doppler)	Wired probe	~2 MHz; ≤ 14 cm	Cardiac tissues; central vessels; CBF	Real-time monitoring	Commercial rigid phased array (Verasonics P4-2v)	Active beam focusing/steering (−20° to +20°); deep-tissue Doppler performance comparable to commercial device	Healthy only; no LV functional quantification Physiological validation
Hu/2023[9]	Healthy volunteers	Orthogonal wearable cardiac imager (B/M-mode + DL)	Wired wearable patch	3 MHz	LV; standard echo views (PLAX, PSAX, A4C, A2C)	Rest/exercise/ recovery	Commercial echocardiography	Automated EDV, ESV, SV, CO, LVEF from continuous LV volume curves; good agreement with commercial echocardiography for LV volume and derived functional indices	Healthy only; limited clinical validation Physiological validation
Zhang/2025[22]	1 adult PFO patient (49 y/o, bicuspid AV)	WISMED wearable US (W30PC)	Wireless wearable patch	Not reported (proprietary)	RV inflow/outflow tract; PFO occluder position	PFO closure (intraprocedural guidance + postop monitoring)	DSA + TEE (conventional PFO guidance)	Continuous hands-free imaging during intervention; real-time device guidance; avoids esophageal intubation	Single case/ Early clinical feasibility
Wang/2025[23]	1 neonate (3.75 kg, GI bleeding, PFO/PDA)	Wearable phased-array echo (P2-5-64, color Doppler)	Wireless wearable patch	3.6 MHz	LV (volume, contractility); standard neonatal views	Perioperative anesthesia + NICU monitoring	Preoperative clinical echocardiography	Continuous contractility and volume assessment; guides fluid management in neonatal setting	Single case/ Early clinical feasibility

US, ultrasound; CBF, cerebral blood flow; LV, left ventricle; DL, deep learning; PLAX, parasternal long-axis; PSAX, parasternal short-axis; A4C, apical four-chamber; A2C, apical two-chamber; EDV, end-diastolic volume; ESV, end-systolic volume; SV, stroke volume; CO, cardiac output; LVEF, left ventricular ejection fraction; PFO, patent foramen ovale; AV, aortic valve; RV, right ventricular; DSA, digital subtraction angiography; TEE, transesophageal echocardiography; GI, gastrointestinal; PDA, patent ductus arteriosus; NICU, neonatal intensive care unit; echo, echocardiography; f/u, follow-up.
Evidence stage is graded as follows: Technical proof-of-concept, demonstration of device functionality in phantoms or very small samples; Physiological validation, evaluation of measurements or physiological responses in healthy volunteers; Early clinical feasibility, preliminary evaluation in patient populations via case series or small-scale clinical studies; Clinical reference-standard validation, systematic evaluation of measurement agreement or diagnostic performance against an established clinical reference method in a clinical cohort.

not been systematically validated [9]. Accordingly, the use of wearable ultrasound for diastolic dysfunction or heart failure with preserved ejection fraction (HFpEF) remains investigational.

Clinical prospects

Potential applications include heart-failure management, perioperative and critical-care monitoring, and cardiac rehabilitation, where function may change over hours to days while conventional echocardiography provides only intermittent snapshots. Continuous SV, CO, LVEF, or other mechanical indices could in principle reveal early deterioration or treatment response. Although segmentation models have been evaluated on clinical conventional echocardiography datasets [20,21], their performance cannot be assumed to transfer to wearable images. Wearable cardiac-function assessment still requires validation in patients with abnormal anatomy, poor acoustic windows, or arrhythmias [9]. However, most representative studies remain feasibility studies in healthy participants, and prospective disease-specific cohorts are scarce. A scoping review of non-invasive wearable technologies for heart failure similarly found that most systems remain at the feasibility stage and that randomized evidence for improved outcomes is limited [24]. Wearable cardiac ultrasound should therefore not yet be considered established for diagnosis, risk stratification, or treatment guidance. Representative studies of wearable cardiac-function monitoring are summarized in table 1.

Continuous Non-Invasive Blood Pressure Monitoring

Blood pressure (BP) is central to cardiovascular risk assessment and hemodynamic management, yet existing methods trade continuity against invasiveness. Cuff-based devices provide validated but intermittent measurements, and ambulatory BP monitoring remains intermittent. Arterial catheters provide beat-to-beat pressure waveforms but are invasive and largely restricted to settings that justify continuous invasive monitoring. Wearable ultrasound offers a distinct approach by directly tracking deep arterial wall motion and diameter changes rather than relying solely on peripheral optical pulse signals.

Continuous BP estimation from arterial wall dynamics

Pulsatile pressure causes cyclic arterial expansion and recoil. Wearable ultrasound can track the near and far arterial walls using pulse-echo measurements, derive time-varying diameter or cross-sectional area, and convert wall motion into a pressure waveform using a vessel pressure-area relationship after reference calibration.

A key advantage is that ultrasound interrogates the artery itself. Radial, brachial, and carotid arteries can be targeted depending on the application. Wang et al. developed an early conformal ultrasound patch that continuously recorded vascular pulse and pressure waveforms from carotid and radial sites using an ultrathin stretchable design [25]. Sempionatto et al. later integrated ultrasound with electrochemical biosensors in an epidermal multimodal patch, allowing hemodynamic measurements to be synchronized with metabolic markers such as lactate and glucose [26]. These early systems also exposed a practical limitation: a narrow acoustic window makes measurements susceptible to small shifts in patch position. Subsequent development has therefore focused increasingly on robust target coverage and tracking during real-world activity.

Local pulse wave velocity (PWV) provides an alternative route to pressure estimation. Zhou et al. used dual-site piezoelectric micromachined ultrasonic transducers (PMUTs) to measure local PWV from pulse transit between two nearby arterial sites and infer continuous BP from vascular mechanics [27]. In human testing, mean absolute errors for systolic and diastolic BP were both below 4 mmHg. The method avoids explicit reliance on a detailed pressure-area calibration curve but still requires initial reference BP calibration.

Clinical validation of wearable ultrasound BP monitoring

A major advance was the progression from proof-of-concept and physiological validation in healthy volunteers toward clinical reference-standard validation in patient cohorts. Zhou et al. developed an improved wearable ultrasound BP sensor with closely spaced acoustic windows and a backing layer designed to improve vessel coverage and suppress unwanted transducer vibration [10]. The study included 117 participants across several protocols. In seven participants, the device tracked BP responses to cycling, limb movement, mental arithmetic, meditation, food intake, and energy-drink consumption, demonstrating its ability to capture rapid hemodynamic changes that intermittent cuff measurements may miss.

In 85 participants, a supine-standing-supine protocol tested dynamic performance during postural change. The device tracked systolic and diastolic BP trends with good agreement with cuff measurements [10]. These data support sensitivity to posture-related BP variation, although diagnostic performance for orthostatic hypotension has not yet been established in an appropriate patient cohort.

More clinically relevant evidence came from 21

patients undergoing cardiac catheterization, in whom wearable measurements were compared with invasive arterial pressure recordings [10]. The device tracked systolic, diastolic, and mean arterial pressure with close agreement with the arterial-line waveform (Table 2), representing the clinical reference-standard validation stage.

Yuan et al. also demonstrated continuous BP monitoring using a skin-adaptive focused ultrasound (SAFU) transducer, including 24-h recording. Stable pressure waveforms were maintained during handgrip and stepping exercises, and measurement error remained below 3 mmHg within a defined range of positional offset, indicating improved tolerance to moderate misalignment [28].

Clinical value and current limitations

The main clinical value of continuous ultrasound BP monitoring is not another isolated BP reading, but access to transient and time-dependent pressure behavior. BP can change substantially over seconds to minutes with posture, exercise, meals, emotional stress, sleep, and medication. Continuous waveforms may characterize the magnitude, rate, and duration of these changes and reduce missed short-lived events. Outside the hospital, this could be useful for studying nocturnal variation, morning surges, activity-related responses, and treatment dynamics.

In perioperative and critical-care practice, trend information and mean arterial pressure often matter more than isolated values. If wearable ultrasound can reliably track BP without arterial cannulation, it may provide an intermediate monitoring tier for patients at risk of hemodynamic deterioration who do not otherwise require an arterial line, including selected postoperative ward and emergency-observation patients.

These potential uses remain largely untested in outcome studies. Existing work demonstrates measurement accuracy and trend tracking but has not shown that continuous ultrasound BP monitoring reduces hypotension duration, cardiovascular events, length of stay, or improves antihypertensive management [29]. The next step is therefore to test clinical utility: whether the additional temporal information changes management and improves outcomes.

A key BP-specific limitation is calibration stability. Most current methods require reference BP calibration, while changes in vascular tone or arterial stiffness may alter the relationship between vessel dimensions and pressure. Validation should therefore establish how long calibration remains reliable and when recalibration is required [30]. Representative studies of continuous ultrasound BP monitoring are summarized in table 2.

Vascular Hemodynamics and Arterial Stiffness

Beyond BP, wearable ultrasound can measure blood-flow velocity, vessel dimensions, and vascular wall mechanics. Its main advantage is the conversion of conventional single-time-point vascular measurements into continuous physiological trajectories.

Continuous blood-flow monitoring

Doppler ultrasound estimates blood-flow velocity from frequency shifts produced by moving erythrocytes. Conventional vascular Doppler generally requires an operator to hold and adjust the probe, whereas wearable systems can maintain a transducer over the target vessel and acquire Doppler spectra with limited intervention.

The carotid artery has been a major target because of its superficial location, relative anatomic stability, and relationship to the central circulation. Wireless wearable systems can continuously acquire carotid Doppler spectra and derive indices such as corrected carotid flow time (ccFT). Kenny et al. studied 19 healthy volunteers undergoing passive leg raising (PLR), analyzing 36 PLR maneuvers and 8,856 Doppler cardiac cycles [11]. ccFT increased within 40-60 s after PLR and showed moderate ability to identify increases in SV. These findings support ccFT as a continuous trend marker of preload-related hemodynamic change rather than a replacement for standard CO monitoring.

Patient studies have further compared wearable carotid Doppler with clinical reference methods. In a proof-of-principle study of patients undergoing coronary artery bypass grafting (CABG), Kenny et al. reported an area under the receiver operating characteristic curve (AUROC) of 0.95 for 10-beat averaged corrected carotid velocity-time integral in detecting a $\geq$ 10% change in stroke volume measured by transesophageal echocardiography (TEE) [31]. A subsequent study evaluated corrected carotid flow time and found that ΔccFT correlated with ΔSV ($r = 0.70$), with the AUC increasing from 0.68 for a single beat to 0.87 after averaging 20 beats [32]. Munding et al. manipulated cardiopulmonary bypass (CPB) pump flow and found that a 10% change in total flow corresponded to an approximately 13.6% change in common carotid artery velocity, supporting the physiological link between carotid Doppler dynamics and systemic flow [33].

Research has subsequently expanded from single velocity measures toward functional hemodynamic phenotyping. Kenny proposed combining ccFT and left ventricular ejection time (LVET) with preload challenges for bedside assessment of fluid responsiveness [34]. Hofer et al. analyzed more than 137,000 wearable

Table 2 Representative studies of wearable ultrasound for continuous non-invasive blood pressure monitoring

Author/year	Population	Device/method	Target vessel	Calibration	Monitoring/duration	Comparator	Key findings	Integration	Evidence stage
Wang/2018 [25]	1 healthy male volunteer	Conformal US patch; pulse-echo arterial wall tracking	Carotid artery + jugular vein	Yes; BP derived from vessel diameter–pressure relationship (brachial cuff for DBP reference)	Rest and exercise; continuous waveform monitoring; up to 2 h skin integration	Commercial tonometry	Continuous central and peripheral arterial pulse/BP waveforms from vessels up to ~4 cm deep; good agreement with tonometry	Wired probe	Technical proof-of-concept
Sempionatto/2021 [26]	Healthy volunteers	Multimodal epidermal patch (US + electrochemical sensors)	Carotid artery	Yes; commercial cuff BP calibration	Food intake, exercise, daily stimuli; continuous simultaneous monitoring	Commercial cuff BP monitor	Simultaneous BP/HR + glucose/lactate/caffeine/alcohol monitoring; detected expected BP/HR responses to exercise and metabolic changes	Wired wearable patch	Physiological validation
Zhou/2025*(IEEE)* [27]	17 healthy subjects (12M/5F, 22-36 y)	Wearable PMUT; pulse-echo arterial diameter + local PWV	Two sites along a single artery (local PWV)	Yes; initial BP cuff calibration required	Rest and dynamic BP changes; wearable/mobile monitoring	Cuff sphygmomanometer; PPG finger clip (waveform)	SBP/DBP MAE <4 mmHg, SD < 3 mmHg; HR error < 3 bpm; waveform r = 0.951-0.998	Wireless wearable (PMUT)	Physiological validation
Lin/2024 [5]	Healthy adult volunteers	Fully integrated USoP (A/B/M-mode + ML target tracking)	Carotid artery/central arteries	Yes; tonometer calibration for BP	Moving subjects; exercise (cycling, HIIT); ≤ 12 h continuous	Tonometer; reference BP devices	ML-based autonomous vascular target tracking (96.13% accuracy with domain adaptation); central BP error < 1.58 mmHg post-calibration; continuous BP/HR/CO	Fully integrated wireless system	Physiological validation
Zhou/2025*(NatBE)* [10]	117 participants (7 daily-activity, 85 outpatient, 21 catheterization, and 4 ICU participants)	Wearable US BP sensor; closely spaced sonographic windows + backing layer; arterial wall-motion sensing	Brachial and radial arteries (main)	Yes; reference calibration used	Daily activities; supine–standing challenge; cardiac catheterization; ICU 10–12 h	Cuff BP; invasive arterial line (cath lab & ICU)	Cath lab: Bland–Altman SBP 0.34 ± 3.90, MAP −0.18 ± 2.20, DBP −0.43 ± 2.66 mmHg; met ISO 81060-2 criteria; outpatient MAD ≤ 4.90 mmHg	Wireless wearable patch	Clinical reference-standard validation
Yuan/2025 [28]	Healthy volunteers; multiple small BP-validation cohorts	SAFU flexible US array (2.4 MHz, self-adhesive hydrogel); arterial wall tracking	Fingertip, radial, brachial, carotid (multi-artery)	Yes; vessel mechanics linked to reference BP	Multi-artery testing, exercise, 24-h BP monitoring	Mercury sphygmomanometer	SBP error 1.8 ± 2.98, DBP error 1.1 ± 2.43 mmHg (representative); 24-h monitoring ±2.48/±1.99 mmHg; robust to moderate misalignment	Flexible wearable patch	Physiological validation

US, ultrasound; BP, blood pressure; DBP, diastolic BP; PMUT, piezoelectric micromachined ultrasound transducer; PWV, pulse wave velocity; PPG, photoplethysmography; SBP, systolic BP; MAE, mean absolute error; SD, standard deviation; HR, heart rate; USoP, ultrasonic-system-on-patch; ML, machine learning; HIIT, high-intensity interval training; CO, cardiac output; ICU, intensive care unit; MAP, mean arterial pressure; ISO, International Organization for Standardization; MAD, mean absolute difference; SAFU, skin-adaptive focused ultrasound; BMI, body mass index; cath, cardiac catheterization.
Evidence stage is graded as follows: Technical proof-of-concept, demonstration of device functionality in phantoms or very small samples; Physiological validation, evaluation of measurements or physiological responses in healthy volunteers; Early clinical feasibility, preliminary evaluation in patient populations via case series or small-scale clinical studies; Clinical reference-standard validation, systematic evaluation of measurement agreement or diagnostic performance against an established clinical reference method in a clinical cohort.

Doppler cardiac cycles to define physiological ranges of LVET across heart rates, age groups, and clinical states [35]. Simultaneous venous-arterial Doppler has also been used to record the internal jugular vein (IJV) and common carotid artery during PLR, generating a 'Doppler Starling curve' that visualizes the coupling between venous return and arterial output [36].

More recent systems combine vessel cross-sectional area with Doppler velocity to estimate volumetric carotid flow. A T-shaped wearable patch reported in 2026 acquired short-axis area and long-axis Doppler information within the same cardiac cycle to estimate carotid flow volume [12]. This approach addresses a key limitation of velocity-only measurements, which can be confounded by changes in vessel caliber. However, these systems remain at the proof-of-concept and physiological validation stages, and their incremental value over conventional Doppler or established CO monitoring has not been shown in large patient cohorts.

Quantitative findings and evidence stages for vascular hemodynamic studies are summarized in table 3. Current evidence therefore supports the ability of wearable ultrasound to acquire continuous vascular velocity and timing signals and to detect selected dynamic hemodynamic changes. Importantly, indices such as ccFT and carotid VTI should be interpreted primarily as trend-tracking biomarkers rather than as absolute quantitative surrogates for cardiac output or fluid responsiveness in individual patient decision-making; many published predictive models lack external validation in independent cohorts. Its accuracy for fluid-responsiveness assessment, CO estimation, or disease diagnosis remains insufficiently established.

Wearable assessment of arterial stiffness

Arterial stiffness reflects structural and functional properties of the vessel wall and is associated with aging, hypertension, and atherosclerosis. Pulse wave velocity (PWV) and local compliance are commonly used measures. Wearable ultrasound can continuously track pulsatile diameter changes and combine them with BP to estimate local arterial stiffness.

Yuan et al. demonstrated this approach using a SAFU transducer [28]. Continuous arterial diameter tracking was combined with BP to calculate the beta stiffness index and local PWV. Hypertensive and older participants showed higher values than their respective controls, whereas athletes showed lower values, indicating sensitivity to differences in local vascular mechanical state.

Wearable PWV measurements showed broadly similar between-subject trends to a clinical arterial-stiffness device, although relative error remained below approximately 25% [28]. Importantly, the methods do not measure the same construct: wearable ultrasound primarily assessed local radial-artery mechanics, whereas conventional arterial-stiffness assessment often uses a longer path such as carotid-femoral PWV (cfPWV). Local ultrasound-derived PWV and cfPWV therefore cannot currently be used interchangeably.

Rather than replacing established stiffness measurements, wearable ultrasound may be more useful for tracking short-term local vascular dynamics during exercise, pharmacological intervention, or circadian variation. Prolonged monitoring could reveal individualized temporal patterns that are inaccessible to isolated PWV measurements.

Current studies support detection of differences in local arterial mechanics, but do not establish diagnostic thresholds for atherosclerosis or cardiovascular risk stratification. The relationship between local ultrasound-derived stiffness measures, standard cfPWV, and cardiovascular outcomes remains to be established.

Overall, wearable vascular ultrasound has progressed from velocity monitoring to flow-time indices, estimated volumetric flow, and local arterial mechanics. Compared with continuous BP monitoring, the evidence remains concentrated at the physiological validation and early clinical feasibility stages. Representative studies are summarized in table 3.

Emerging Cardiovascular and Hemodynamic Applications

Wearable ultrasound is also being explored for cerebral blood flow, venous hemodynamics, acute and critical care, therapeutic stimulation, and fetal monitoring. These applications are generally less mature than continuous BP monitoring and should currently be interpreted primarily in terms of feasibility and level of validation.

Continuous transcranial cerebral blood-flow monitoring

Cerebral hemodynamic monitoring is relevant to neurocritical care, stroke, subarachnoid hemorrhage, and perioperative management. Transcranial Doppler (TCD) can measure intracranial arterial flow velocity non-invasively, but conventional examinations depend on an operator to locate and maintain an adequate acoustic window.

Zhou et al. developed a conformal transcranial ultrasound patch capable of continuous monitoring through the temporal window and three-dimensional Doppler reconstruction of major intracranial vessels [13]. In 36 healthy volunteers, peak systolic, mean, and end-diastolic velocities showed good agreement with conven-

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Table 3 Representative studies of wearable ultrasound for vascular hemodynamics and arterial stiffness assessment

Study	Population	Device	Target	Key parameter	Comparator	Key quantitative finding	Integration	Evidence stage
Kenny/2023 *Front Biosci Elite* [11]	19 volunteers; 36 PLR	Wireless CW Doppler patch	Carotid	ccFT	Non-invasive pulse-contour SV	8,856 cycles; ccFT tracks SV change (AUROC 0.77 for +5% ΔSV)	Wireless patch	Physiological validation
Kenny/2021 *Bioengineering* [31]	2 CABG patients (proof-of-principle)	Wireless CW Doppler patch (4 MHz)	Carotid	ccVTIΔ	TEE	10-beat averaged ccVTIΔ: AUROC 0.95 for +10% ΔSV	Wireless patch	Early clinical feasibility
Kenny/2025 *CHEST Crit Care* [32]	CABG patients (post-op)	Wireless CW Doppler patch	Carotid	ΔccFT	TEE ΔSV	Validated ΔccFT for detecting ≥ 10% SV change	Wireless patch	Clinical reference-standard validation
Munding/2023 [33]	14 on-pump CABG patients	Hands-free CW Doppler patch	Carotid	Max CCA velocity	CPB pump flow	13.6% ΔCCA velocity ↔ 10% ΔCPB flow	Hands-free patch	Early clinical feasibility
Kenny/2023 *Ultrasound J* [36]	2 illustrative cases (1 healthy + 1 clinical)	Wireless CW Doppler patch (4 MHz)	Carotid + IJ vein	ccFT, VTI, venous Doppler	Non-invasive SV (case 1); clinical context (case 2)	"Doppler Starling curve" framework; differential preload-output responses	Wireless patch	Early clinical feasibility
Hofer/2025 [35]	347 participants; 137,521 cycles	Wireless CW Doppler patch	Carotid	ccFT/LVET (4 correction equations)	— (reference distribution)	Mean ccFT 295–311 ms across correction formulas; 99.1% signal validity across 137,521 cycles	Wireless patch	Physiological validation
Kong/2026 [12]	In vitro + human volunteers	Wearable T-shaped B-mode + Doppler patch (8.5 MHz, 1.3 mm)	Carotid	CSA + VTI → volumetric flow	Commercial US system	In vitro max deviation 6.3%; simultaneous dual-axis imaging	T-shaped array patch	Physiological validation
Yuan/2025 [28]	Paired subgroups (n = 2 per pair): HT/normo, elderly/young, athlete/sedentary	SAFU flexible pulse-echo array (2.4 MHz)	Radial (stiffness); multiple sites (BP)	β-stiffness index, local PWV	Arteriosclerosis detector (VBP-9)	HT β = 13.1 vs normo β = 9.9; PWV relative error < 25%	Flexible self-adhesive array	Early clinical feasibility
Li/2026 [37]	In vitro phantom only	Stretchable PW Doppler patch (5.05 MHz, 6 transducers, ~30% stretch)	Flow phantom	Flow velocity	Reference pump velocity	MAE 3.56 cm/s, MAPE 5.99% (20-100 cm/s)	Stretchable patch	Technical proof-of-concept

PLR, passive leg raising; CW, continuous-wave; ccFT, corrected carotid flow time; SV, stroke volume; AUROC, area under the receiver operating characteristic curve; CABG, coronary artery bypass grafting; TEE, transesophageal echocardiography; CCA, common carotid artery; CPB, cardiopulmonary bypass; IJ, internal jugular; VTI, velocity-time integral; LVET, left ventricular ejection time; CSA, cross-sectional area; US, ultrasound; HT, hypertension; SAFU, skin-adaptive focused ultrasound; BP, blood pressure; PWV, pulse wave velocity; PW, pulsed-wave; MAE, mean absolute error; MAPE, mean absolute percentage error; ccVTI, carotid velocity-time integral; Δ, change.

Evidence stage is graded as follows: Technical proof-of-concept, demonstration of device functionality in phantoms or very small samples; Physiological validation, evaluation of measurements or physiological responses in healthy volunteers; Early clinical feasibility, preliminary evaluation in patient populations via case series or small-scale clinical studies; Clinical reference-standard validation, systematic evaluation of measurement agreement or diagnostic performance against an established clinical reference method in a clinical cohort.

tional TCD, and monitoring was sustained for up to 4 h. The overall measurement success rate was 70.6%, similar to 75.3% for conventional TCD, indicating that wearable implementation does not eliminate skull attenuation or interindividual limitations of the temporal acoustic window.

Evidence remains dominated by healthy participants, with little systematic validation in stroke, subarachnoid hemorrhage, or vasospasm. Wearable transcranial ultrasound has therefore established proof-of-concept and physiological validation but has not reached early clinical feasibility in patient populations.

Venous congestion and non-invasive assessment of central venous pressure

Central venous pressure (CVP) reflects right atrial pressure and systemic venous filling. Standard measurement requires central venous catheterization, motivating non-invasive approaches based on ultrasound assessment of superficial central veins [38].

The IJV changes with right atrial pressure and can be assessed by ultrasound through cross-sectional area and respiratory variation. In 2026, Dong et al. reported a prospective multicenter study of 349 ICU patients using AI-assisted wearable ultrasound to image the IJV and common carotid artery, with catheter-measured CVP as the reference [14]. Automated vessel segmentation and cross-sectional-area features, combined with basic clinical variables, were used to identify elevated CVP ($\geq$ 8 mmHg). The study demonstrated clinically relevant discrimination of elevated CVP in real ICU populations.

Continuous imaging may eventually support longitudinal assessment of venous filling, but current evidence validates classification of elevated CVP rather than continuous, precise replacement of invasive CVP monitoring. A more realistic near-term role is adjunctive trend assessment or early warning in lower-acuity settings, while invasive monitoring remains necessary when high-fidelity pressure measurement is required, such as selected cardiac-surgical or extracorporeal membrane oxygenation (ECMO) settings.

Continuous hemodynamic monitoring in acute and critical care

Hemodynamics can change rapidly in emergency, perioperative, and critical-care settings. Bedside ultrasound provides valuable structural and functional information but is intermittent and operator dependent, whereas invasive monitors are not appropriate for every patient. Wearable ultrasound could occupy an intermediate role by continuously tracking BP, CO-related signals, and cardiac mechanics with limited operator input.

Building on autonomous cardiovascular monitoring during movement [5], clinical studies have extended wearable ultrasound BP monitoring to catheterization-laboratory and ICU patients, including 10-12 h comparisons with invasive arterial pressure in a small postoperative ICU cohort [10]. Evidence in complex critically ill populations remains limited.

Wearable carotid Doppler has also been evaluated during fluid administration. Kenny et al. analyzed 86 fluid challenges in 51 emergency-department patients and found that some infusions produced no expected carotid hemodynamic response, suggesting a potential role for identifying physiologically ineffective fluid loading [39]. The observational design, however, does not establish reduced fluid exposure or improved outcomes. In trauma resuscitation, Da Luz et al. prospectively studied 33 severely injured patients; successful placement and analyzable data were obtained in 31. Transfused patients showed lower ccFT and spent longer periods at low ccFT values, but the study was not designed to establish ccFT as a predictor of major hemorrhage or a transfusion-guidance tool [40].

Hands-free carotid Doppler has also been investigated during cardiopulmonary resuscitation. In a two-centre pilot study involving 62 cardiac-arrest patients, Doppler recordings were analyzed in 36 patients and demonstrated detection of compression-generated blood flow and spontaneous circulation, including return of spontaneous circulation (ROSC). Patch fixation and cable-related device deficiencies remained practical limitations [41].

Continuous cardiac imaging has also entered perioperative case-based practice. A 2025 report described wearable ultrasound during patent foramen ovale (PFO) closure, providing continuous visualization of right-heart structures and procedural changes as an adjunct to intermittent transthoracic imaging [22]. Another case report used wearable ultrasound during general anesthesia and postoperative neonatal intensive care unit (NICU) monitoring to follow ventricular filling and contraction [23]. These reports demonstrate clinical feasibility in settings where repeated handheld examinations are difficult, but they do not establish comparative efficacy.

The more important opportunity in acute care may be integration rather than accumulation of individual parameters. Arterial pressure, cardiac pump function, arterial flow, and venous congestion describe complementary aspects of circulation. A future wearable platform capable of aligning these signals on the same time axis could provide a more informative hemodynamic phenotype than any single measure. The proposed Safe and Fluid Effective Resuscitation (SaFER) framework similarly combines venous excess ultrasound (VExUS), velocity-time integral (VTI), and venous/arterial

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Doppler information to assess preload response and venous congestion, although it remains a conceptual and protocol-based framework without randomized-trial validation [42].

Wearable ultrasound pacing

Wearable ultrasound is also being explored as a therapeutic modality. In 2026, Gong et al. reported a non-invasive sonogenetic pacing system [43]. Adeno-associated viral delivery was used to express the mechanosensitive ion channel MscL-G22S in cardiomyocytes, increasing their sensitivity to focused ultrasound pulses delivered from a chest-mounted wearable array and enabling controlled myocardial depolarization.

In animal models, the system enabled targeted stimulation of different cardiac regions and effective pacing in bradycardia, conduction-block, and arrhythmia models. Long-term follow-up did not identify major myocardial injury or inflammatory abnormalities, supporting preclinical feasibility.

Sonogenetic pacing remains purely preclinical, with the available evidence limited to animal models. It relies on adeno-associated viral gene delivery to express ultrasound-responsive ion channels in cardiomyocytes. Major hurdles before human therapeutic use include uncertain efficiency and specificity of gene delivery to human cardiomyocytes, immune risks, and unknown long-term safety of channel expression and repeated ultrasound stimulation. Integration of sensing and therapy within a wearable platform remains a long-term research prospect. Sonogenetic pacing should therefore be viewed as a preclinical proof-of-concept rather than a near-term clinical alternative to established pacing.

Fetal cardiovascular monitoring

Fetal cardiovascular physiology is highly dynamic. Conventional fetal monitoring primarily records heart rate, whereas diagnostic ultrasound is intermittent and operator dependent. Wearable ultrasound is therefore being explored for continuous assessment of fetal hemodynamics.

In 2026, Park et al. reported UPatch, a wearable ultrasound platform for autonomous monitoring in high-risk pregnancy [44]. The abdominal patch continuously acquired fetal anatomy and flow signals, while real-time segmentation tracked fetal and umbilical structures and derived umbilical-artery flow indices and fetal heart rate. In prospective testing, the systolic/diastolic ratio, pulsatility index, resistance index, and fetal heart rate showed good agreement with handheld clinical ultrasound. In one preeclampsia case, abnormal umbilical-flow fluctuations were detected while fetal heart rate remained within the normal range, suggesting that continuous flow monitoring may reveal placental-circulatory abnormalities not captured by heart rate alone.

Fetal wearable ultrasound remains at a very early clinical-validation stage. Key technical bottlenecks include the lack of fully wireless platforms, signal instability caused by fetal movement and variable maternal acoustic windows, and the absence of robust external validation for automated hemodynamic interpretation—where false alerts could carry serious clinical consequences. Ethically and regulatorily, fetal monitoring must meet an especially high safety bar for repeated acoustic exposure, and AI-based interpretation introduces unresolved clinical-liability questions. No evidence to date shows improved pregnancy outcomes or replacement of conventional obstetric ultrasound. Its present value lies primarily in demonstrating feasibility and the potential to capture transient abnormalities between scheduled examinations.

Clinical Challenges to Translation

Progress in cardiac function, BP, and hemodynamic monitoring does not by itself establish readiness for routine care. Clinical translation requires stable long-term operation, reliable measurements across heterogeneous patients, and evidence that the resulting information adds value to decision-making. The central question is therefore shifting from whether wearable ultrasound can measure continuously to whether those measurements are trustworthy, interpretable, and clinically actionable.

Signal stability and reproducibility

Continuous monitoring requires stable and reproducible signal acquisition without constant manual probe adjustment. Acoustic coupling, mechanical fixation, and positional stability relative to the target therefore directly determine data quality.

Bioadhesive hydrogel interfaces have supported continuous human attachment and imaging for up to 48 h [18], but dehydration, perspiration, friction, and skin deformation can still degrade the interface. Evaluation should therefore extend beyond wear time to include analyzable-signal yield, recovery after signal loss, between-day reproducibility, and reproducibility after patient self-reapplication. Analyzable-signal yield is inconsistently reported across studies. In the secondary analysis by Hofer et al., 136,339 of 137,521 recorded cardiac cycles (99.14%) met the analysis criteria of heart rate $\leq$ 250 beats/min and valid ccFT; this proportion does not establish analyzable-signal availability over the total monitoring duration [35]. Without adequate reproducibility, changes in PWV, flow velocity, or BP may reflect probe position rather than physiology.

Practical usability also requires evaluation of who can reliably apply the device. Hands-free monitoring after successful placement does not establish that hospital staff without specialized ultrasound training or patients themselves can independently identify the acoustic window and attach the patch correctly. In the trauma feasibility study by Da Luz et al., the device was placed by trained research personnel rather than the primary clinical team [40]. Future studies should therefore evaluate initial placement and reapplication by the intended users, reporting training requirements, placement time, successful acquisition of analyzable signals, and the need for expert assistance. For home monitoring, clear placement instructions and real-time feedback on acoustic contact and target acquisition may support self-application, but their effectiveness requires prospective usability validation.

Validation against clinical reference standards

Reference methods vary substantially across wearable-ultrasound studies. Some studies assess image quality or correlation, others compare with cuff BP, conventional TCD, or commercial ultrasound, and a smaller number use invasive arterial pressure or central venous catheter measurements. This heterogeneity limits cross-study comparison.

For quantitative measures, correlation is not equivalent to agreement. Validation of continuous BP, CO, flow velocity, or CVP should emphasize bias, Bland-Altman agreement, repeatability, and trend concordance rather than correlation coefficients or AUROC alone. The fetal study by Park et al., for example, used Bland-Altman analysis to compare wearable and clinical ultrasound measurements [44].

Beyond agreement with the reference method, validation of continuous monitoring should assess trend accuracy, response time, long-term drift, and event-detection performance[30]. An important limitation of the current evidence base is that nearly all validation studies have been conducted by the device-developing teams themselves. This introduces a risk of developer-originated bias, as investigators who design and build a device may have implicit incentives to demonstrate favorable performance. Few studies have been replicated by independent clinical groups using external cohorts, and no large-scale, independently conducted multicenter validation has been established for any wearable ultrasound platform. Such independent replication is essential to confirm that reported performance generalizes beyond the settings, operators, and patient populations in which the device was originally developed. Future research should prioritize prospective, independently led validation studies with prespecified protocols and blinded outcome assessment to reduce this bias.

Generalizability across patient populations

Many representative studies have been conducted in young, healthy participants with favorable acoustic windows. Real-world patients show substantially greater variation in body mass index (BMI), subcutaneous tissue thickness, vessel depth, vascular calcification, chest-wall anatomy, emphysema, cardiac enlargement, and temporal-bone thickness.

These factors affect applications differently. Obesity may reduce signal-to-noise ratio for deep cardiac or vascular imaging; arterial stiffening or calcification may alter pressure-diameter relationships used for BP estimation; arrhythmias may disrupt algorithms that assume regular cardiac cycles; and transcranial monitoring remains constrained by temporal-window quality.

Algorithmic generalizability is equally important, and current claims regarding AI-assisted wearable ultrasound should be interpreted with caution. Automated segmentation, target tracking, and parameter estimation depend heavily on the populations, anatomical variability, and devices represented in training data. While published AI models often report high accuracy on their own test sets, these results may not translate to clinically unselected populations, unusual anatomy, or suboptimal signal quality. Many studies also lack prospective, blinded evaluation against clinical reference standards, and head-to-head comparisons with human expert performance remain scarce. Future validation should therefore include clinically heterogeneous cohorts, independent external testing, and prespecified subgroup analyses in older adults, patients with obesity, hypertension, heart failure, atrial fibrillation, and hemodynamic instability. Broad adoption will require robust performance in these more difficult populations.

Clinical actionability of continuous data

Continuous monitoring produces large volumes of images, waveforms, and quantitative parameters, but more data do not necessarily translate into greater clinical value [29]. The key questions are which variables warrant continuous monitoring, what magnitude or pattern of change is clinically meaningful, and when an intervention should be triggered.

Normal ranges and actionable thresholds remain undefined for many wearable-ultrasound metrics. Transient changes in LVEF, local PWV, or CVP-related indices may reflect physiology, artifact, or disease. Wearable systems therefore need to progress from continuous measurement toward validated event detection that distinguishes physiological variability and motion artifact from clinically important change.

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Low-specificity alerts may also cause alarm fatigue and increase clinical workload. Scholte et al. noted that many wearable-monitoring technologies lack validated decision thresholds [24], while remote-monitoring literature similarly emphasizes that data acquisition is useful only when abnormality thresholds and response pathways are clearly defined [45]. To limit this burden, monitoring systems should filter artifacts and flag unreliable measurements before generating alerts. Adaptive thresholds that account for the patient's baseline and the persistence of abnormal changes require clinical validation. Electronic health-record integration should present clinically relevant trends and events with signal-quality information, rather than require routine review of all raw recordings. Clear responsibilities for reviewing alerts and initiating a response are also essential.

Future studies should therefore move beyond measurement accuracy toward management and outcome endpoints. Relevant questions include whether continuous BP monitoring reduces unrecognized hypotension, whether continuous cardiac assessment detects deterioration earlier, and whether wearable Doppler improves fluid management. These questions require prospective management studies and, ultimately, randomized trials.

Safety, standardization, and regulatory considerations

Prolonged acoustic exposure is a distinctive safety issue for wearable ultrasound. Conventional diagnostic ultrasound is generally used for minutes, whereas wearable devices may operate continuously or repeatedly for hours or longer.

Safety evaluation should therefore report not only instantaneous mechanical index (MI) and thermal index (TI), but also duty cycle, cumulative exposure, local temperature rise, and long-term skin reactions. Short-term human studies have not identified major safety signals: Yuan et al. reported skin-surface temperature variation within 1.5°C during 24 h testing [28], and Wang et al. reported temperature increases within the tested safety range during 48 h imaging [18]. However, available human safety data remain limited to wear periods of hours to a few days, and evidence establishing the safety of continuous application over weeks is lacking. These short-term findings should therefore not be extrapolated to prolonged use. Several populations also warrant specific attention. Fetal exposure raises unique safety concerns: the developing fetus is considered more sensitive to thermal and mechanical effects of ultrasound, and continuous or repeated exposure over hours—far exceeding the duration of standard diagnostic scans—has not been adequately studied for potential effects on fetal growth, tissue development, or long-term outcomes. The ALARA (as low as reasonably achievable) principle and thermal index monitoring remain essential, but safety experience from conventional intermittent obstetric examinations does not establish the safety of prolonged wearable exposure [46]. Pediatric and neonatal applications similarly require heightened caution: thinner skin and smaller body dimensions alter acoustic propagation and temperature distribution, and immature tissue may be more vulnerable to prolonged acoustic exposure. Until dedicated safety data exist, wearable ultrasound in fetal and pediatric populations should be applied under conservative output settings and with explicit risk-benefit justification. Repeated long-term exposure across all populations requires prospective evaluation. Song et al. have called for wearable-ultrasound-specific safety frameworks addressing acoustic output, cumulative thermal dose, and chronic skin-contact biocompatibility [6].

Standardization is equally important. Minimum reporting standards should include proportion of analyzable signal/valid data, probe position, operating frequency, monitoring duration, reference method, signal-quality criteria, and failure modes. Without consistent reporting, cross-study comparison, meta-analysis, and eventual guideline development will remain difficult [47]. Analyzable-signal yield is particularly critical for wearable devices, as it directly reflects real-world usability and distinguishes devices that function reliably under clinical conditions from those that perform well only under idealized settings.

Real-world implementation also depends on economic and practical factors rarely discussed in the current literature. Consumable costs—including adhesive hydrogel coupling layers, disposable transducer interfaces, and single-patient-use patches—remain unclear for most wearable ultrasound platforms, and repeated replacement could substantially accumulate expenses over prolonged monitoring. Beyond thermal risk, prolonged skin contact with hydrogel–elastomer coupling layers and adhesive interfaces may cause irritation or contact dermatitis, potentially limiting comfort and adherence. Evidence for long-term skin compatibility of wearable ultrasound remains limited to short-duration studies [18], and systematic evaluation of comfort, wearability, and skin reactions across diverse age groups and skin types is lacking.

Conclusion

Wearable ultrasound is emerging as a platform for continuous, hands-free cardiovascular monitoring by providing information that conventional wearables can-

not directly capture, including cardiac mechanics, arterial pressure, blood-flow dynamics, and local vascular properties. Continuous cuffless BP monitoring has the most mature clinical validation overall. Most other applications remain at the physiological validation or early clinical feasibility stage, although selected measures, including the identification of elevated CVP, have undergone clinical reference-standard validation.

The key translational challenge is no longer simply whether continuous signals can be acquired, but whether they remain reliable across time and patients and whether they improve clinical decisions. There is still a lack of clinical-outcome-oriented evidence, and it has not yet been proven that measurements derived from wearable ultrasound can improve patient-relevant clinical endpoints. By organizing current evidence according to validation maturity and clinical reference standards, this review highlights the shift required from engineering feasibility toward reproducible, actionable, outcome-relevant monitoring.

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Authors' Contributions

ZC W, XQ S and PL R conceived of and designed the study; XH drafted the manuscript; XM and XH participated in and completed the literature collection; FX Y and XH performed the research; LK C acquired and interpreted of the data for the work. All authors contributed to editorial changes in the manuscript. All authors read and approved the final manuscript.

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Data sharing is not applicable to this article as no datasets were generated or analyzed during the current study.

Declarations

Ethics approval and consent to participate

This study is a review article that does not involve original research with human participants, animal subjects, or clinical data. Therefore,ethics approval and informed consent are not applicable

Conflict of interest

The authors have no conflict of interest to declare.

Consent for publication

Not applicable.

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