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Review

Cardiovascular Abnormalities in Daily Life: Digital Monitoring, Wearables, and the Early Course of Disease

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Abstract

Wearable devices and other forms of digital monitoring have extended cardiovascular observation beyond the clinic; however, the clinical value of these devices is not captured by describing them merely as convenient versions of Holter monitors, blood pressure cuffs, or pulse oximeters. Their distinctive contribution lies in repeated measurement during ordinary life, across sleep, activity, recovery, symptoms, and day-to-day physiological variation. This shifts the clinical question. Instead of asking only whether a cardiovascular abnormality is present at the time of testing, clinicians may begin to ask how an abnormality develops, fluctuates, and resolves within the baseline and lived context of an individual. Atrial fibrillation provides the clearest proof of concept, because wearable-based detection is clinically meaningful only when photoplethysmography-derived alerts are recognized as screening signals, followed by electrocardiographic confirmation, and integrated into risk-based clinical care. Large, pragmatic studies and contemporary guidance now support several components of this pathway. Yet the significance of digital cardiovascular medicine extends beyond atrial fibrillation. Heart failure decompensation, blood pressure lability and autonomic fluctuation, sleep-related cardiovascular burden, and the evaluation of palpitations or nonspecific symptoms may all benefit from longitudinal, context-rich observation. False positives, uncertain actionability, user anxiety, data overload, uneven access, and weak interoperability remain substantial constraints. The mature clinical promise of the field lies not in technology alone, but in enabling cardiovascular abnormalities to be examined in daily life, during their early course, and in relation to the individual in whom they occur.

Keywords: cardiovascular diseases; wearable electronic devices; mobile applications; telemedicine; artificial intelligence; atrial fibrillation; heart failure; blood pressure monitoring, ambulatory; photoplethysmography

1. Introduction

Cardiovascular medicine has long depended on episodic observation. Blood pressure is measured during a visit. Rhythm is sampled during a symptomatic episode, a scheduled electrocardiogram, or a finite monitoring period. Symptoms are reconstructed after the fact, often with imperfect recall. This model remains indispensable, but it also limits what clinicians can observe. Many cardiovascular abnormalities are intermittent, situational, or slow to emerge. They may appear during sleep, exertion, emotional strain, recovery, or ordinary daily activity rather than during a scheduled clinical encounter.

The safe clinical use of ambulatory digital data requires standards for interoperability, provenance, metadata, and workflow [1]. Recent reviews and scientific statements have emphasized both the clinical promise and the practical strain created by wearable and mobile technologies in cardiovascular care, while distinguishing passive monitoring, patient-triggered recordings, clinically validated applications, and consumer wellness functions [2,3,4,5,6]. The central issue is therefore not whether digital monitoring is newer or more convenient than conventional testing. It is whether repeated observation in ordinary life can help clinicians understand cardiovascular abnormalities that are otherwise difficult to capture. Such observation may reveal timing, recurrence, burden, recovery, and the relation of physiological signals to symptoms, behavior, and environment. It may also place a signal against the individual's own recent baseline rather than against a single population threshold.

This framing is especially relevant because cardiovascular care increasingly extends attention toward earlier disease states. The 2023 atrial fibrillation (AF) guideline recognizes stages that precede clinically established arrhythmia and emphasizes risk-factor modification and earlier recognition. The 2024 ESC/EACTS guideline further emphasizes electrocardiographically confirmed diagnosis, risk-based stroke prevention, and targeted AF screening in older or otherwise higher-risk populations [7,8]. The 2022 heart failure guideline likewise highlights Stage A and Stage B disease, reinforcing that prevention and preclinical disease identification are part of cardiovascular medicine [9]. Digital monitoring aligns with this broader shift, but its value depends on whether signals are interpretable, confirmable, and clinically actionable.

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AF is the most developed example. Large pragmatic studies have shown that wearable platforms can generate photoplethysmography (PPG)-derived irregular rhythm notifications at population scale and that a meaningful proportion of those notifications correspond to electrocardiogram (ECG)-confirmed AF when confirmatory monitoring is obtained [10,11]. Yet AF should not be mistaken for the entire field. Its importance is methodological as much as clinical: it shows what becomes possible when repeated, low-burden monitoring meets a condition that is intermittent, often silent, and clinically consequential. The same logic, with less mature evidence, extends to heart failure decompensation, blood pressure and autonomic fluctuation, sleep and recovery-related cardiovascular burden, and symptom evaluation in daily life.

The strongest current evidence lies in wearable-based detection and confirmatory pathways for AF. Heart failure monitoring is promising but less mature, while cuffless blood pressure monitoring still belongs more to development and validation than to routine cardiovascular management [6,7,12,13]. This uneven evidentiary landscape warrants explicit acknowledgment because the maturity of the field differs substantially across clinical domains. The evidence base is anchored by a relatively small number of landmark trials, statements, and concept-shaping studies (Table 1, Ref. [1,3,6,7,10,11,12,13,14,15,16,17,18,19,20,21,22]).

Accordingly, this review examines how wearable and other digital monitoring technologies can extend cardiovascular assessment from episodic testing to longitudinal observation in daily life. We use AF as the most mature clinical example and then consider heart failure decompensation, blood pressure and autonomic fluctuation, sleep and recovery, and symptom evaluation, with particular attention to individual baseline, signal confirmation, clinical actionability, and integration into care pathways. We also highlight the main gaps that currently limit broader clinical adoption, including uneven validation across devices and clinical domains, uncertain thresholds for intervention, workflow and interoperability challenges, and the need to distinguish informative monitoring from data that are not yet sufficiently reliable or actionable for routine care.

2. Why Wearables Change the Unit of Observation

Wearables are often introduced by analogy. They are described as simplified Holter monitors, cuffless blood pressure monitors, or wrist-based pulse oximeters. The analogy is understandable, but it is incomplete. A wearable does not derive its clinical meaning solely from the accuracy of a single measurement compared with a conventional instrument. Its added value lies in persistence. A device that collects a modestly accurate signal many times a day, across changing circumstances, may answer a different question from a device that measures more precisely but only briefly and under controlled conditions. That is one reason recent statements in this field emphasize workflow, context, data quality, and interpretation rather than diagnostic accuracy alone [1,3,6].

Continuous or near-continuous observation creates three forms of clinical information that have been relatively scarce in conventional practice. The first is temporal pattern. Rhythm abnormalities, heart rate shifts, activity decline, and sleep disruption become interpretable as recurring or nonrecurring, abrupt or gradual, isolated or clustered. The second is contextual pattern. The signal can be viewed alongside sleep timing, physical activity, posture, symptoms, and recovery. The third is internal reference. Instead of asking only whether a value crosses a population threshold, clinicians can ask whether it has deviated from that person's recent baseline. These distinctions indicate that the traditional framework of one-time diagnostic substitution does not fully capture the clinical value of repeated, context-rich observation [2,3].

This does not mean that every continuously measured signal is clinically useful. Many are proprietary composites with uncertain physiological meaning. Consumer wearables differ widely in hardware, sampling strategy, artifact handling, calibration, and output definitions. Some outputs are interpretable only within a given device ecosystem. Regulatory status also differs across devices and, importantly, across functions within the same device. Certain wearable or handheld electrocardiographic functions—for example, selected Apple Watch electrocardiogram functions and dedicated Kardia electrocardiogram systems—have received regulatory authorization, clearance, or medical-device certification in particular jurisdictions. In contrast, many activity, sleep, oxygen-saturation, stress, recovery, and proprietary wellness outputs have not been authorized as diagnostic medical-device functions. Regulatory status should therefore be described at the level of the specific function, model, software version, intended use, and jurisdiction rather than being attributed to an entire brand or platform. This distinction affects the evidentiary standard, expected reliability, labeling, and degree of confidence appropriate for clinical decision-making [23]. The 2024 Journal of the American College of Cardiology (JACC) scientific statement and the 2024 American Heart Association (AHA) interoperability statement both draw attention to these problems, particularly when data are exported into clinical workflows without clear standards for provenance, quality, or meaning [1,6]. The key issue is identifying which forms of repeated data are clinically interpretable and under what conditions.

This clinical shift reflects a change in the unit of observation. Conventional care often centers on the encounter or test, whereas digital cardiovascular medicine increasingly follows the individual over time. This shift has direct clinical consequences. A patient with intermittent palpitations may no longer be evaluated only by whether an in-clinic electrocardiogram is normal. A patient with heart failure

Table 1. Selected landmark studies and key statements relevant to digital cardiovascular monitoring.

Study or statement	Year	Type	Main relevance
Promises and Perils of Consumer Mobile Technologies in Cardiovascular Care [6]	2024	JACC Scientific Statement	Defines the field's main opportunities and its central risks, including nonactionable data, workflow burden, and overmedicalization
Data Interoperability for Ambulatory Monitoring of Cardiovascular Disease [1]	2024	AHA Scientific Statement	Establishes interoperability, provenance, metadata, and workflow as major clinical constraints
Consumer Wearable Health and Fitness Technology in Cardiovascular Medicine [3]	2023	State-of-the-art review	Provides broad cardiovascular framing while preserving clinical nuance
2023 ACC/AHA/ACCP/HRS Guideline for the Diagnosis and Management of AF [7]	2024	Guideline	Anchors AF diagnosis, confirmation, and staged thinking
Apple Heart Study [11]	2019	Large pragmatic siteless study	Proof that consumer wearables can identify plausible AF signals at scale
Fitbit Heart Study [10]	2022	Large pragmatic wearable study	Extends large-scale passive AF detection in a distinct consumer platform
VITAL-AF [14]	2022	Cluster-randomized screening trial	Tests AF screening in primary care and helps define where screening may be more or less persuasive
SCREEN-AF [15]	2021	Randomized clinical trial	Adds evidence on AF screening in older populations
mAFA-II [16,22]	2021 (main results) / 2022 (secondary analysis)	Randomized mHealth-integrated care trial and later analyses	Shows that digital information matters most when embedded in integrated care
LINK-HF [12]	2020	Multicenter observational proof-of-concept	Illustrates personalized baseline and multisensor drift before HF rehospitalization
Impact of a Novel Wearable Sensor on Heart Failure Rehospitalization [17]	2024	Open-label concurrent-control clinical trial	Suggests that noninvasive wearable HF monitoring may influence rehospitalization outcomes in selected settings
HERMeS [18]	2025	Multicenter randomized trial	Supports the importance of telemonitoring plus teleintervention rather than passive monitoring alone
ESH statement on cuffless blood pressure measuring devices [13]	2022	Society statement	Defines why cuffless BP still requires caution
ESH recommendations for validation of cuffless BP devices [19]	2023	Society recommendations	Sharpens methodological standards for future clinical use
Sleep patterns and risk of chronic disease as measured by long-term monitoring with commercial wearable devices in the All of Us Research Program [20]	2024	Prospective cohort study	Supports the relevance of sleep pattern as cardiovascular context
Sleep regularity as an important component of sleep hygiene [21]	2025	Systematic review	Helps justify sleep regularity as a specific contextual construct rather than a generic lifestyle variable

Abbreviations: AF, atrial fibrillation; AHA, American Heart Association; BP, blood pressure; ECG, electrocardiogram; ESH, European Society of Hypertension; HF, heart failure; JACC, Journal of the American College of Cardiology; mHealth, mobile health.

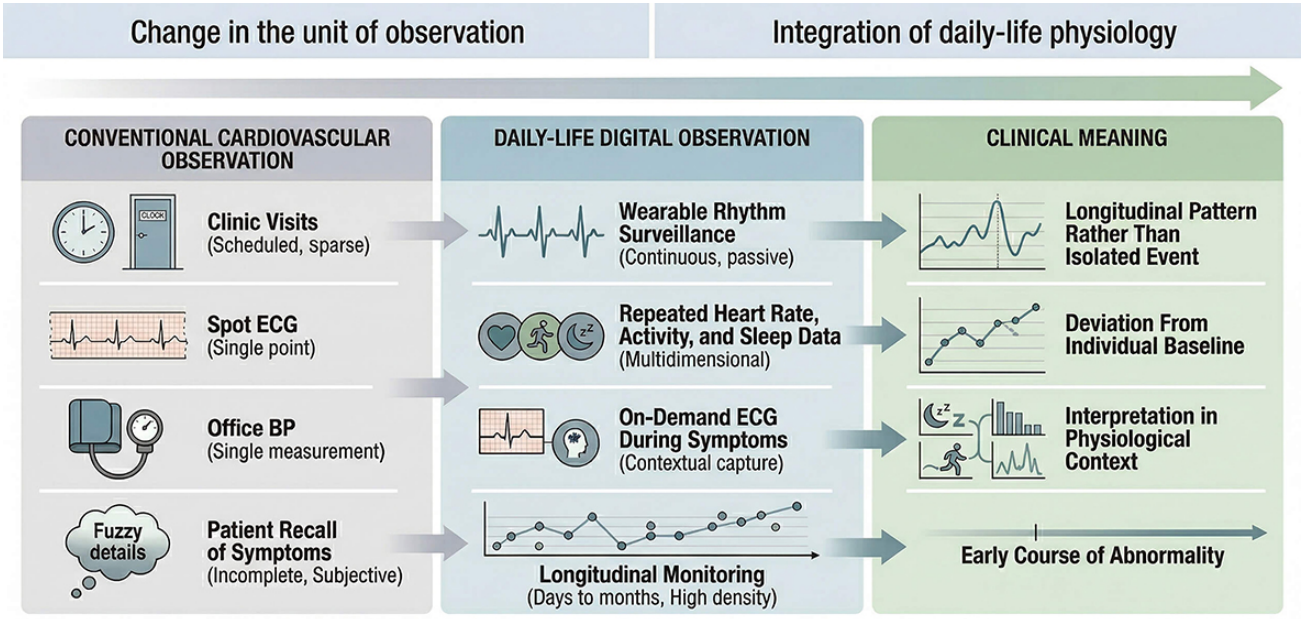


Fig. 1. How digital monitoring changes the clinical unit of observation in cardiovascular medicine. The figure contrasts conventional episodic cardiovascular assessment with daily-life digital observation and highlights four interpretive consequences of this shift: recognition of longitudinal pattern, deviation from individual baseline, interpretation in physiological context, and attention to the early course of abnormality. **Abbreviations:** BP, blood pressure; ECG, electrocardiogram.

may not be represented only by weight and symptoms reported at follow-up. A person with elevated stroke risk may not remain invisible until AF is captured opportunistically. Wearables make these intervals more visible, but clinical value depends on deciding when the resulting observations are trustworthy enough to justify action. This conceptual shift—from episodic assessment to longitudinal, context-rich observation in daily life—is summarized in Fig. 1.

3. Interpreting Longitudinal Physiology: Baseline, Drift, and State Change

Repeated measurement is clinically useful only if clinicians move beyond threshold thinking. Population thresholds remain indispensable in diagnosis and management, but they are not the whole story when data are dense and individualized. Digital monitoring invites a different layer of interpretation: whether a signal has changed relative to the person's own established range, whether multiple signals are changing together, and whether those changes precede symptoms, coincide with them, or occur independently. That style of reasoning is already familiar in some parts of medicine. The novelty here is that it may be applied to ambulatory physiology outside tightly supervised settings.

Artificial intelligence (AI) is frequently introduced in this context, often before the underlying clinical questions are fully defined. In its most restrained and clinically meaningful form, AI is useful because it can help organize longitudinal data that are too frequent, noisy, and multidimensional for unaided inspection. Its more clinically useful role may be to interpret physiological drift, recurrent states, and individualized patterns over time, rather than only to classify events after they occur [6,24]. A system that learns the expected nightly heart rate, sleep timing, activity level, and signal variability of one person may be more helpful than a system that compares every user against a universal threshold. Even so, the literature remains stronger for classification than for short-horizon forecasting, and stronger for selected use cases than for broad clinical generalization [6,24].

The language of baseline deserves care. An individual baseline is not a substitute for standards of care, nor does it eliminate the need for medical confirmation. It acknowledges that physiology varies widely across individuals and that longitudinal change may carry information even when the absolute value remains within a conventional reference range. This idea is supported indirectly by several bodies of work. In heart failure, the LINK-HF study used a personalized baseline derived from multisensor data after hospital discharge and identified patterns associated with rehospitalization before overt clinical deterioration [12]. In rhythm monitoring, automated interpretation of single-lead electrocardiograms in VITAL-AF was associated with subsequent incident AF, suggesting that digital traces may hold signals of vulnerability as well as contemporaneous diagnosis [25]. These findings do not prove that all meaningful physiology is best captured by individualized modeling, but they justify taking the concept seriously.

In clinical use, an individual baseline should be treated as a reference range built from stable, good-quality data

rather than as a single personal average. The baseline window should be long enough to capture ordinary variation, but short enough to remain relevant to the patient's current treatment, activity level, sleep pattern, and disease state. A deviation from baseline should first prompt checks of signal quality, device use, medication changes, intercurrent illness, and symptom timing. It becomes more clinically persuasive when several signals change together, when the change is sustained or recurrent, and when it is consistent with the patient's risk profile or known disease. Even then, baseline deviation should guide triage and interpretation rather than replace established diagnostic confirmation [6,12].

Some physiological domains are more mature than others. Heart rate itself is easy to capture but difficult to interpret in isolation. Heart rate variability is appealing because it may reflect autonomic balance and recovery, yet it is sensitive to recording conditions, artifact, duration, and processing choices. A 2023 head-to-head study found that smartwatch-derived heart rate variability showed high concordance with electrocardiogram-derived measures for selected parameters under standardized conditions, which is encouraging [26]. Current evidence does not support treating consumer heart rate variability metrics collected in uncontrolled settings as stable clinical biomarkers. The gap between technical validity and clinical meaning remains substantial. Similar caution applies to sleep metrics. Consumer wearables can characterize timing and some aspects of sleep behavior with increasing sophistication, but their cardiovascular role is currently stronger as contextual information than as direct treatment targets [20,27].

State change is a central concept in this field, but current claims often exceed the available evidence. The attractive hypothesis is that a patient moves through a sequence of preclinical or transitional states before overt decompensation, symptomatic arrhythmia, or clinically recognized burden. Repeated digital observation might reveal these states early enough to inform prevention or timely intervention. The hypothesis is conceptually plausible, but the supporting evidence remains uneven. For AF, short-term pre-episode signatures and near-term onset prediction are still investigational [28]. For heart failure, multisensor drift before rehospitalization is plausible and partly demonstrated, but routine care pathways have not yet caught up [12,17]. Dense observation is necessary for early recognition, but it does not establish that early recognition is already clinically reliable.

4. Atrial Fibrillation as Proof of Concept

No condition has done more than AF to clarify both the promise and the limits of digital cardiovascular monitoring. Several features of AF make this particularly evident. AF is common, often intermittent, and frequently asymptomatic. Importantly, the absence of symptoms does not indicate a lower need for thromboembolic risk assessment. A meta-analysis including 81,462 patients found no significant differences in stroke or combined stroke and thromboembolic events between asymptomatic and symptomatic AF, supporting management according to the patient's thromboembolic-risk profile rather than symptomatic status [29]. AF is also clinically important because of its associations with heart failure, hospitalization, and reduced quality of life. It is unusually well suited to digital study because the signal of interest is cardiac rhythm itself and because confirmation can be anchored to established electrocardiographic standards. That combination has made AF the first cardiovascular disorder in which wearables, mobile platforms, and digital pathways have moved from novelty to sustained clinical debate [6,7]. Fig. 2 summarizes AF as a model case spanning established applications, emerging uses, and investigational frontiers.

The Apple Heart Study marked an early turning point. In a large pragmatic siteless study, irregular pulse notifications were uncommon, and among participants who underwent subsequent ambulatory electrocardiographic confirmation, the positive predictive value for AF was high enough to demonstrate that user-owned devices could identify plausible rhythm abnormalities outside traditional care settings [11]. The Fitbit Heart Study reinforced this observation in another large wearable ecosystem, showing that photoplethysmography-based irregular rhythm detection could identify participants with electrocardiographically confirmed AF and appreciable arrhythmia burden [10]. These studies did not establish that mass consumer screening improves hard outcomes. They showed that passive, low-burden PPG monitoring can identify individuals with signals suggestive of silent or intermittent AF at population scale while keeping false alerts low enough to remain clinically relevant. A photoplethysmography-derived irregular-pulse notification is a screening signal only; it cannot establish the diagnosis of AF or independently justify anticoagulation or another AF-specific treatment.

The screening literature has matured since those initial demonstrations. In VITAL-AF, point-of-care single-lead electrocardiogram screening in primary care did not produce a broad overall screening mandate, but it sharpened the question of which older adults might benefit most from targeted case finding [14]. Other randomized or pragmatic screening studies in older populations have similarly suggested that the value of screening depends heavily on age, baseline risk, monitoring modality, and the downstream care pathway [15]. The emerging evidence suggests a narrower interpretation than many early reports implied. Wearable-based AF screening becomes clinically persuasive when it is directed toward a population in whom earlier diagnosis could reasonably alter management, and when the path from alert to confirmation is already in place.

Detection, diagnosis, and management are not interchangeable steps. A photoplethysmography-derived irregular-rhythm notification indicates possible AF but is not an electrocardiographic tracing and cannot estab-

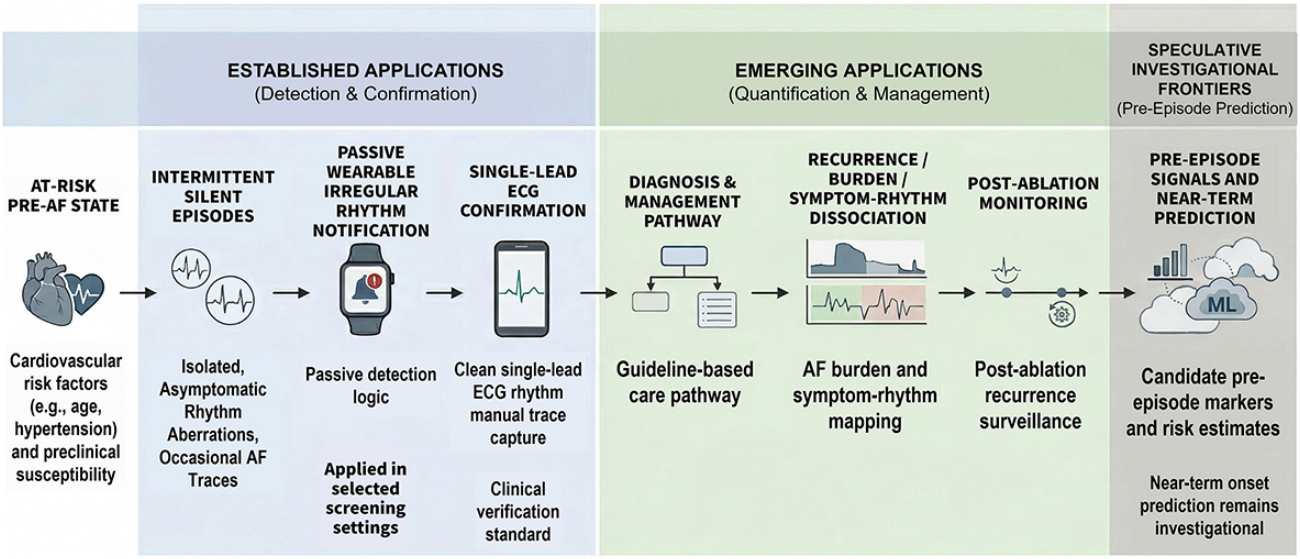


Fig. 2. Atrial fibrillation as a model case for longitudinal digital cardiovascular monitoring. AF provides the clearest current example of how wearable and digital monitoring can move from detection toward longitudinal characterization and care integration. The left side of the figure represents more established applications, including passive irregular-rhythm notification and single-lead electrocardiographic confirmation. The middle section represents emerging applications, in which monitoring contributes to diagnosis and management pathways, recurrence and burden assessment, symptom-rhythm dissociation, and selected post-ablation surveillance. The right side identifies areas that remain investigational, particularly the use of candidate pre-episode markers and short-horizon prediction of impending onset. The figure distinguishes clinically established uses from emerging applications and investigational frontiers, clarifying the current maturity of digital monitoring in AF. Photoplethysmography-derived irregular-rhythm notifications are screening signals rather than diagnostic tracings and require electrocardiographic confirmation before AF is clinically diagnosed. **Abbreviations:** AF, atrial fibrillation; ECG, electrocardiogram; ML, machine learning.

lish the diagnosis. Clinical AF should be confirmed by an interpretable electrocardiographic recording, such as a 12-lead electrocardiogram, a clinician-interpreted single-lead electrocardiogram, or an ambulatory electrocardiographic recording, before the patient is labeled as having AF and before routine AF-specific treatment decisions are made [7,30]. Management is a third step, involving thromboembolic-risk assessment and stroke prevention, symptom control, treatment of comorbidities, and follow-up. The clinical gain from digital monitoring therefore comes from moving an appropriate patient through a structured sequence of suspicion, electrocardiographic confirmation, risk assessment, and care [7,31].

The principal clinical rationale for AF screening is not detection alone, but the opportunity to prevent thromboembolism in patients whose management may change after electrocardiographically confirmed diagnosis. Under the 2024 ESC/EACTS framework, oral anticoagulation is recommended in patients with confirmed AF and a CHA_2DS_2-VA score of 2 or more and should be considered when the score is 1 [30,32]. Older adults and individuals with additional stroke-risk factors therefore represent a particularly high-yield population for wearable-supported case finding, especially when an established pathway exists from the initial alert to electrocardiographic confirmation and anticoagulation assessment. Nevertheless, neither a photoplethysmographic alert nor an unconfirmed algorithmic classification should directly trigger anticoagulation. Decisions concerning device-detected subclinical AF also remain individualized according to episode characteristics, thromboembolic risk, bleeding risk, and the reliability of rhythm documentation.

Single-lead electrocardiographic capability has strengthened the AF use case because it narrows the distance between consumer monitoring and medical confirmation. Studies of smartwatch-derived single-lead tracings show generally good accuracy for identifying AF when recordings are interpretable [33,34,35]. Newer work also suggests that algorithmic analysis of smartwatch electrocardiograms may further improve arrhythmia detection under some conditions [36]. This does not erase limitations related to user technique, noninterpretable tracings, motion artifact, or baseline ECG abnormalities. Noninterpretable tracings remain clinically relevant, and recent work suggests that underlying ECG abnormalities can substantially affect the yield of consumer single-lead recordings [37]. The practical value of smartwatch electrocardiography lies in narrowing the gap between clinical suspicion and documentable rhythm diagnosis.

Validation studies also matter because they expose the field's real-world edges. The BASEL Wearable Study, which directly compared several direct-to-consumer devices, reminded clinicians that performance is not uniform across devices and conditions [38]. More recent comparative validation work has reinforced that consumer wearables should not be treated as interchangeable diagnostic tools, even when they are marketed for similar rhythm-monitoring functions [39]. Photoplethysmography remains central to passive surveillance, but its accuracy depends on signal quality, motion conditions, and the presence of competing rhythm abnormalities or ectopy [40]. These are not minor technical caveats. They shape who should be monitored, how alerts should be interpreted, and how much diagnostic confidence can reasonably be assigned before formal confirmation.

An important issue is whether digital monitoring contributes more than case finding. AF is often described in binary terms—present or absent—but its temporal expression is not binary. AF episodes vary in frequency, duration, and symptom burden. Some patients remain intensely symptomatic during brief episodes; others have substantial burden with little awareness. That symptom-rhythm dissociation is not a nuisance detail. It is part of the disease. Wearables may help reveal it by linking symptoms to rhythm data across repeated episodes in ordinary life rather than relying on retrospective narrative alone [6]. For the patient with recurrent palpitations, the practical question is often not whether symptoms exist, but whether symptoms coincide with AF, another rhythm disorder, sinus tachycardia, or no rhythm abnormality at all.

AF burden moves rhythm assessment beyond a dichotomous present-or-absent classification. It is generally defined as the proportion of monitored time spent in AF, expressed as a percentage during a specified and explicitly reported monitoring period; where clinically relevant, the duration of the longest uninterrupted AF episode should also be reported [41]. Monitoring duration and continuity are integral to interpretation because intermittent sampling may substantially overestimate or underestimate true burden. Symptoms cannot be used as a surrogate for burden, as substantial AF may occur without awareness and prominent symptoms may occur during sinus rhythm or brief episodes. Longitudinal burden assessment may help characterize disease progression, recurrence after ablation, symptom–rhythm dissociation, and associations with stroke, heart failure, hospitalization, and quality of life. However, clinically actionable thresholds are likely to be outcome- and population-specific and remain insufficiently established for many wearable applications. Burden estimates derived from intermittently sampled consumer devices should therefore not automatically be considered equivalent to continuous implantable or medical-grade monitoring.

Preliminary registry data suggest that very early AF detected by a wearable electrocardiographic patch after ablation may predict later blanking-period recurrence [42]. More recent post-ablation studies suggest that smartwatch-based monitoring can estimate AF burden and may show partial convergence with more continuous monitoring strategies, although clinically actionable thresholds remain unsettled [43,44]. Recovery studies using personal digital devices have also shown that physical activity and symptoms can provide a more textured picture of post-procedural recovery than routine follow-up alone [45]. These observations are clinically attractive because they align with questions electrophysiologists already ask: Is the patient improving? Is recurrence sporadic or sustained? Do symptoms track burden? Yet the evidence is not mature enough to standardize management on smartwatch-derived burden alone. Uncertainty remains about how these estimates compare with implantable monitoring, how much burden is clinically actionable in a given context, and which patients truly benefit from this degree of surveillance.

Pre-episode signatures and near-term onset prediction occupy an earlier stage of development. There is legitimate scientific interest in whether subtle changes in heart rate, autonomic tone, activity, sleep, or short-run rhythm irregularity might anticipate AF onset. The VITAL-AF analysis showing that automated single-lead electrocardiographic interpretations predict incident AF points toward the possibility that digital signals may carry information about vulnerability before clinically recognized disease [25]. AI-based sinus-rhythm ECG models for future AF risk add to that impression [28]. A substantial gap remains between identifying enriched risk and forecasting an impending episode with sufficient reliability to guide day-to-day therapeutic decisions. Present evidence supports the idea that digital monitoring can characterize vulnerability and recurrence patterns. It does not yet justify strong claims about routine pre-episode warning systems or device-triggered treatment strategies outside research settings.

AF also illustrates why detection must be connected to care. In mAFA-II and its later analyses, mobile health-supported care improved outcomes when digital tools were used within an integrated framework rather than as isolated alerts [16,22]. The clinical benefit arose from structured anticoagulation assessment, symptom management, comorbidity treatment, and follow-up. Pragmatic work in AF-adjacent settings, including smartphone-based photoplethysmography monitoring after cardiac surgery, points in the same direction: rhythm detection is most useful when linked to a defined management pathway rather than treated as an isolated technical success [46]. Data acquire value when they enter a clinical architecture; without that architecture, increased detection may lead to uncertainty, testing, and patient burden without proportional clinical benefit.

AF therefore serves as the field's clearest proof of concept in two senses. It shows that wearable

monitoring can identify clinically meaningful abnormalities outside conventional encounters, and it shows that early or repeated recognition matters only when confirmatory and therapeutic pathways are available. These considerations also apply to other areas of digital cardiovascular medicine. The broader significance of wearable and digital monitoring becomes clearer when the same interpretive framework is applied beyond AF to other clinical settings in which longitudinal, context-rich observation may be informative (Table 2, Ref. [7,10,11,12,13,17,18,19,20,21,34,38,39,42,43,44,47,48,49,50,51,52,53,54,55,56,57,58]).

5. Beyond AF: Other Clinical Domains Where Context Matters

5.1 Heart Failure Decompensation

Heart failure is an obvious target for digital monitoring because decompensation usually develops over time rather than appearing without warning. Symptoms worsen gradually, activity contracts, sleep is disrupted, resting physiology shifts, and subtle congestion may precede overt hospitalization. The problem has always been that these changes are distributed across daily life and are often nonspecific when considered one at a time. A single weight measurement or symptom call may miss the broader pattern. Wearables are attractive here because they can sample multiple physiological and behavioral domains repeatedly and with relatively little burden. Available platforms include chest patches, wrist-worn devices, textile or garment-based sensors, smart scales, and other connected systems capable of repeated or continuous assessment of heart rate and rhythm, respiratory rate or respiratory pattern, physical activity, posture, sleep, body weight, oxygen saturation, and, in selected systems, thoracic impedance or other congestion-related surrogates [59]. Their potential value lies less in any isolated vital sign than in coordinated and sustained change across several physiological and behavioral signals. Recent review work has also helped clarify which noninvasive digital biomarkers may be most clinically plausible in heart failure, including serial changes in weight, heart rate, activity, and other physiologic surrogates when interpreted longitudinally rather than in isolation [49].

The LINK-HF study remains the clearest early demonstration of this approach. Using a chest patch and continuous multisensor monitoring after hospitalization for heart failure, investigators developed personalized baselines and identified patterns associated with impending rehospitalization before overt clinical deterioration [12]. The study's significance lies less in the specific model than in the logic it operationalized. Heart failure deterioration may be better recognized as coordinated physiological drift within an individual than as any single metric crossing a universal threshold. That proposition remains clinically persuasive because it fits the lived course of many patients and the frequent mismatch between symptom reporting and the biology of worsening congestion.

Recent evidence has made this argument more concrete, although not definitive. A 2023 review emphasized that home monitoring for heart failure is most useful when serial measurements are organized into clinical signals rather than read as isolated values [47]. In a 2024 open-label concurrent-control trial, a wearable sensor platform was associated with fewer heart failure rehospitalizations in a selected care setting [17]. HERMeS, a multicenter randomized trial published in 2025, added a further point: telemonitoring was paired with teleintervention, so the observed benefit reflected an organized care model rather than passive sensing alone [18]. A meta-analysis of remote multiparameter monitoring also suggested benefit, but its findings were limited by heterogeneity in devices, populations, monitoring intensity, and response pathways [51].

These data support a cautious clinical position. Wearable and digital heart failure monitoring is best viewed as a strategy for selected patients and organized programs rather than as a general outpatient standard. The unresolved issues are practical: which signals should trigger contact, who reviews them, how quickly a response is expected, and how false alarms are managed. Patient and caregiver engagement may be part of the effect, making workflow and education inseparable from sensing performance [48]. Until larger real-world programs and more consistent trial evidence define trigger thresholds and response protocols, heart failure remains a strong candidate for individualized longitudinal monitoring, but not yet a fully operationalized routine pathway [50].

5.2 Hypertension and Autonomic Fluctuation

Blood pressure would seem an ideal digital target because hypertension is prevalent, often silent, and tightly linked to long-term cardiovascular events. Daily-life blood pressure behavior also matters. Morning surges, nocturnal pressure, stress-related rises, and lability across the day may all carry clinical meaning. For these reasons, cuffless or low-friction blood pressure monitoring continues to attract attention. This is also the part of digital cardiovascular medicine where methodological caution needs to be strongest.

Cuffless devices can generate blood pressure estimates. The clinical question is whether those estimates are sufficiently robust, reproducible, and interpretable in real-world conditions to support the diagnostic and treatment decisions that currently depend on established measurement methods. The 2022 European Society of Hypertension statement and the 2023 validation recommendations are clear on this point: cuffless devices face substantial challenges related to calibration, body position, movement, physiological drift, device-specific algorithms, and the distinction between tracking change and measuring absolute pressure accurately [13]. A recent review of emerg-

Table 2. Clinical domains in which wearable and digital monitoring may add cardiovascular information.

Clinical domain	Signals and context of interest	What is already clinically useful	What is promising but not yet routine	Main cautions
Atrial fibrillation	Irregular rhythm notifications, single-lead ECG, symptom-triggered ECG, longitudinal rhythm burden, recurrence after ablation	Detection of possible AF, ECG-based confirmation, targeted screening in selected higher-risk groups, symptom-rhythm correlation, selected post-ablation surveillance [7,10,11,42]	Burden estimation, individualized recurrence patterning, more structured post-ablation remote follow-up, refined patient-led monitoring strategies [43,44]	PPG-derived irregular-rhythm alerts are not diagnostic; ECG confirmation is required before clinical AF labeling and routine AF-specific treatment. Device performance varies, and the management implications of very low-burden AF remain uncertain [7,38,39]
Heart failure decompensation	Resting heart rate, respiratory pattern, activity decline, sleep disruption, oxygen saturation, body weight, posture, and selected congestion-related surrogates, multisensor drift, digital biomarkers over days to weeks	Proof-of-concept for early deterioration signals; growing evidence that structured remote monitoring may support vulnerable-phase management [12,17,47]	Personalized baseline deviation models, telemonitoring linked to teleintervention, and practical outpatient escalation pathways [18,48,49]	Heterogeneous devices and workflows, uncertain trigger thresholds, modest implementation evidence, benefit may depend on surrounding care infrastructure [50,51]
Hypertension and autonomic fluctuation	Repeated BP estimates, resting HR, HRV, orthostatic changes, diurnal variation, movement context	Conventional cuff-based home and ambulatory BP monitoring remain standard; wearable HR/HRV may provide contextual background [13,19,52]	Characterization of BP variability and daily-life hemodynamic patterns; integration of movement and timing context into interpretation [53,54]	Cuffless BP validation remains incomplete; consumer metrics should not replace established methods for diagnosis or treatment titration [13,19]
Sleep, stress, and recovery	Sleep duration, timing, regularity, fragmentation, nocturnal HR, HRV-derived recovery signals	Sleep-related data can improve contextual interpretation of symptoms and cardiovascular strain [20,55]	Integration of longitudinal sleep and recovery patterns into individualized cardiovascular interpretation [21,56,57]	Device-specific metrics, uncertain clinical thresholds, risk of overmedicalizing wellness outputs, opaque composite scores
Palpitations and nonspecific symptoms	On-demand ECG, HR trend, symptom-linked recordings, symptom diary linked to wearable data	Arrhythmia capture during symptoms, reassurance when rhythm is normal during symptoms, better symptom-rhythm correlation [34,58]	Richer contextual interpretation of intermittent symptoms in daily life	Limited diagnostic scope beyond rhythm; chest discomfort should not be overinterpreted through consumer data

Abbreviations: AF, atrial fibrillation; BP, blood pressure; ECG, electrocardiogram; HR, heart rate; HRV, heart rate variability; PPG, photoplethysmography.

ing sensing and modeling technologies for wearable and cuffless blood pressure monitoring reflects rapid technical progress, but it also reinforces how development has outpaced clinical standardization [54]. Ambulatory cuff-based blood pressure monitoring therefore remains the reference standard for many diagnostic and management questions in hypertension [52].

At present, cuffless blood pressure devices should be discussed as an area of active development rather than as substitutes for established methods used to diagnose or titrate treatment for hypertension [13,19]. Overstatement in this area would materially misrepresent the current state of the evidence.

Repeated low-burden blood pressure estimation may still offer clinically meaningful insight by making visible

aspects of cardiovascular loading that are sparsely sampled by office, home, or ambulatory cuff measurements. This could matter for patients with pronounced lability, orthostatic syndromes, autonomic dysfunction, or blood pressure patterns tightly linked to sleep, activity, and stress. Recent device-based analyses of 24-hour movement behaviors and blood pressure support the broader idea that blood pressure in daily life may be better understood when interpreted alongside the behavioral pattern in which it is embedded, rather than as an isolated hemodynamic value [53]. It may also matter in the earlier stages of cardiovascular risk, where daily-life hemodynamic behavior is already becoming abnormal before sustained hypertension is fully established. The current evidence does not support routine substitution. It does support continued interest in pattern characterization and in the possibility that blood pressure interpretation may one day become more temporally and physiologically nuanced than it is now.

Autonomic fluctuation occupies a related but less codified territory. Resting heart rate, heart rate variability, and recovery metrics may reflect stress, sleep loss, illness, deconditioning, medication effects, and broader autonomic state. These signals are attractive because they can be tracked against recent personal baseline. Yet they are heavily context-dependent. The strongest present use of such metrics is as explanatory background rather than as standalone decision instruments. A shift in nocturnal heart rate or heart rate variability may help explain why symptoms, perceived exertion, or blood pressure variability behave differently over a given week. It should not yet be treated as a discrete therapeutic target unless tied to a clearer clinical framework [26].

5.3 Sleep, Stress, Recovery, and Cardiovascular Burden

Sleep has become a major part of the wearable ecosystem, and cardiovascular medicine has good reason to pay attention. Sleep timing, duration, regularity, and fragmentation are associated with hypertension, obesity, diabetes, arrhythmia risk, and cardiovascular events. Recent device-based cohort work has also linked jointly measured sleep characteristics and habitual movement patterns to cardiometabolic risk markers, reinforcing the value of interpreting cardiovascular physiology against the broader behavioral structure of daily life [56]. Consumer devices are increasingly capable of tracking sleep-related behavior over long periods. This is useful because many cardiovascular symptoms and physiologic changes are interpreted too thinly when sleep and recovery are ignored.

The evidence in this domain remains heterogeneous, requiring careful interpretation. Large observational work continues to support an association between healthier sleep patterns and lower cardiovascular risk [20,27]. More recent literature has sharpened interest in sleep regularity as a distinct component of sleep health rather than merely a derivative of duration [21]. These findings are relevant to cardiovascular medicine because they reinforce the notion that physiology in daily life is not random background noise. It is structured by behavior, timing, and recovery. A patient's nocturnal heart rate, sleep regularity, or activity restoration may provide important context for interpreting palpitations, resting tachycardia, perceived exertional decline, or broader cardiovascular strain. This contextual role may be particularly relevant in older adults with heart failure, where device-assessed sleep health has begun to reveal an additional layer of physiological burden that routine follow-up often captures only indirectly [57].

Wearable sleep metrics should not be overmedicalized. Consumer sleep staging, readiness scores, and proprietary stress composites are not equivalent to validated cardiovascular biomarkers. At present, their most defensible clinical role is contextual. They help explain the physiological background in which symptoms and abnormalities arise. They may clarify whether a rise in resting heart rate follows sleep debt, whether episodic symptoms cluster after several nights of disrupted sleep, or whether reduced recovery tracks with broader cardiovascular instability. This contextualization is modest in appearance but clinically meaningful. One of the recurring weaknesses of conventional cardiovascular assessment is that it captures symptoms and vital signs with little visibility into the behaviorally structured setting in which they occur.

Stress-related outputs warrant especially cautious interpretation. Many consumer platforms now provide composite stress or recovery scores, but these remain partly opaque and device-specific. They may be useful as personal feedback tools but are not validated cardiovascular endpoints. Sleep timing, recovery pattern, and background physiological strain offer more clinically tractable constructs than device-specific composite scores.

5.4 Palpitations, Chest Discomfort, and Nonspecific Symptoms in Daily Life

One of the most immediate clinical uses of wearable rhythm technology is not screening but symptom interpretation. Palpitations are common, unsettling, and often intermittent. Traditional ambulatory monitoring works well when symptoms recur during the monitoring window; it is less helpful when events are brief, infrequent, or difficult to predict. Smartphone-based or wearable event recorders improve this situation by allowing patients to capture electrocardiographic data at the time of symptoms. That has clear practical value, even when the resulting diagnosis is no arrhythmia at all.

The larger contribution is interpretive. These tools can help distinguish symptoms accompanied by rhythm abnormality from symptoms that are not rhythm-mediated. This distinction matters in recurrent palpitations, episodic presyncope, or fluctuating awareness of the heartbeat. It also matters in AF, where symptom-rhythm dissociation is common and where patient experience often diverges

from objective burden [58]. A device that documents sinus rhythm during symptoms may be as helpful as one that captures AF, because it narrows the differential and can redirect evaluation. Daily-life monitoring can therefore refine the interpretation of symptom narratives that would otherwise remain clinically ambiguous.

Symptom interpretation also depends on mechanisms that are not captured by rhythm data alone. Interoception, anxiety, autonomic tone, sleep loss, medications, and physical conditioning can all influence how cardiovascular sensations are perceived and reported. This helps explain why some patients feel severe palpitations during brief sinus tachycardia or isolated ectopy, whereas others have substantial AF burden with few symptoms. Wearable data are useful in this setting because they can place symptoms beside rhythm, heart rate, activity, and recovery context. They do not explain symptom perception by themselves, but they can reduce the uncertainty created when symptoms are assessed only through delayed recall [6,58,60].

Chest discomfort requires a narrower discussion. Wearables may be useful when chest symptoms coexist with palpitations, tachycardia, or another concern about rhythm. They are not established tools for diagnosing myocardial ischemia in ambulatory daily life. The concern extends beyond technical limitations to the risk of conceptual overreach. Once a device appears to collect many forms of physiology, it becomes tempting to assume broad diagnostic authority. Clinical interpretation should remain correspondingly narrow.

6. From Signal to Action: Clinical Pathways and Use Across Populations

Digital cardiovascular monitoring becomes clinically meaningful only when a signal has a destination. Clinical use requires decisions about who should be monitored, which abnormalities warrant confirmation, which data justify reassurance alone, and which patterns should trigger formal testing, closer review, or treatment adjustment. These decisions are often treated as implementation details, but they are central to the field. Fig. 3 summarizes the pathway from digital signal detection to clinical action, while highlighting recurrent failure points that may erode actionability.

Recent European expert discussion has converged on a similar conclusion in arrhythmia care: the main challenge is no longer whether digital rhythm data can be generated, but how they should be filtered, integrated, and acted upon within real clinical systems [61].

Three broad clinical groups are worth distinguishing, although the boundaries between them are not rigid. The first is patients with established cardiovascular disease. Here wearables can contribute to follow-up, symptom-rhythm correlation, selected burden estimation, and some forms of post-treatment surveillance. The second is minimally symptomatic or intermittently symptomatic individuals, in whom conventional testing often misses transient abnormalities. The third is people without established disease but with elevated risk or subtle physiological deviation. The ethical stance in this last group must remain measured. The aim is not to medicalize ordinary life. It is to recognize that cardiovascular disease often declares itself late, whereas vulnerability and intermittent abnormality may be present earlier [7,9].

AF again provides the clearest operational model. Photoplethysmographic screening can raise suspicion, but a photoplethysmographic alert alone cannot diagnose AF. Electrocardiographic confirmation remains required before clinical labeling and routine AF-specific treatment. After confirmation, the usefulness of the digital pathway depends on whether it connects the patient to CHA_2DS_2-VA-based thromboembolic-risk assessment, appropriate stroke prevention, symptom management, treatment of comorbidities, and follow-up. Studies of integrated care, including mAFA-II and subsequent analyses, suggest that mobile health improves care when it is used within such a structure rather than as a detached alert stream [16,22]. Later narrative work on AF screening has reached a similar practical conclusion: detection alone is not a care model [62]. Earlier mobile health (mHealth) work in AF also emphasized that digital tools function best as part of structured follow-up rather than as a detached data stream [63].

This same principle applies beyond AF. A possible signal of heart failure worsening becomes useful only if there is a plan for review and response. A change in sleep pattern or recovery is useful only if it sharpens interpretation rather than adding diffuse concern. A wearable blood pressure estimate becomes useful only if the reader knows where it sits relative to more established measurement standards. Actionability is a central determinant of clinical value in digital cardiovascular medicine. A signal has value when it leads to a reasonable next step whose likely benefit exceeds the cost of responding. This is why large parts of the wearable data stream will remain informative rather than decisional for the near future.

7. Limits, Harms, and Conditions for Responsible Use

Digital monitoring cannot be judged only by sensing performance or diagnostic yield. Its limitations and potential harms are already visible, and some are as clinically consequential as the technologies themselves.

False positives remain a fundamental issue. In AF, their frequency depends on prevalence, user characteristics, sensing modality, and the algorithm's threshold for notification. Motion artifact, ectopy, and other rhythm abnormalities complicate passive surveillance [38,40]. Similar issues appear outside arrhythmia. A cuffless blood pressure estimate that drifts after calibration or performs poorly in ordinary use can produce a false sense of precision. A re-

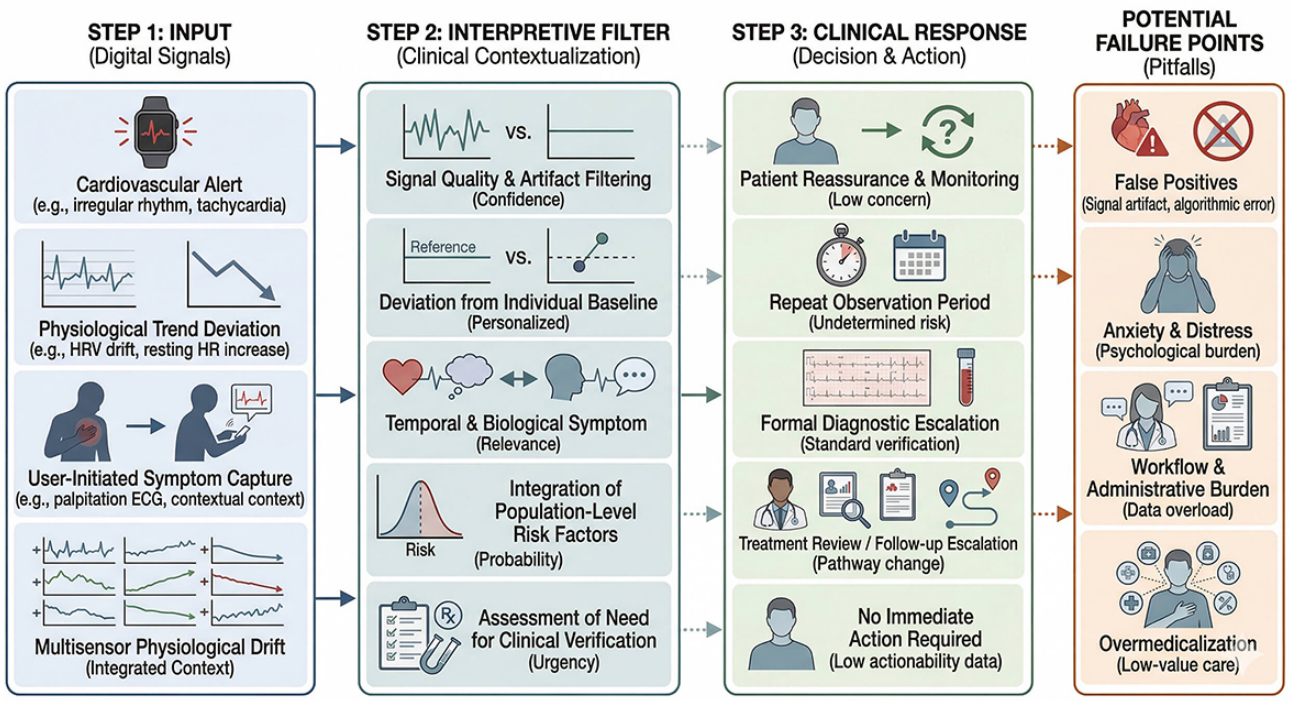


Fig. 3. From digital signal to clinical action: interpretation, response, and common failure points. Digital cardiovascular monitoring becomes clinically meaningful only when a signal is interpreted within context and linked to a response pathway. Digital inputs, including alerts, symptom-linked recordings, physiological trend deviation, and multisensor drift, are filtered through signal quality, individual baseline, symptom relevance, broader risk context, and the need for clinical verification. For suspected AF, this specifically requires electrocardiographic confirmation rather than reliance on a photoplethysmographic alert alone. These steps may lead to reassurance, repeated observation, formal diagnostic escalation, treatment review, follow-up escalation, or no immediate action. Common failure points include false positives, anxiety, workflow burden, and overmedicalization when monitoring is not embedded within a coherent clinical pathway. **Abbreviations:** ECG, electrocardiogram; HR, heart rate; HRV, heart rate variability.

covery score may feel authoritative while resting on opaque assumptions. Validation in controlled conditions does not eliminate these problems [13,19].

Psychological burden deserves more attention than it often receives in technology-focused reviews. In a 2024 study of patients with AF, wearable users reported more symptom monitoring and preoccupation, more treatment concerns, and greater use of health care resources than nonusers [60]. This finding does not support a blanket conclusion that wearables are harmful. It does show that being monitored changes illness experience. In some patients, this may be reassuring or empowering. In others, it may heighten vigilance, uncertainty, and repeated reassurance-seeking. Psychological well-being should be integrated into clinical outcome assessments of digital monitoring rather than being treated as a secondary concern.

Data overload is the corresponding burden on clinicians and health systems. Patient-generated data become less useful when they arrive without standardization, triage logic, interoperability, or reimbursement structures for review [1,6]. Each additional monitoring stream creates work: reviewing alerts, explaining uncertain results, ordering confirmatory tests, documenting decisions, and managing expectations. Without deliberate process design, measurement may expand faster than clinical interpretability.

Equity is another persistent concern. Wearable ownership and sustained use are shaped by cost, digital literacy, language, smartphone access, broadband access, and trust in health systems. At the same time, emerging work in geographically remote and historically underserved populations suggests that wearables may still have practical value when implementation is adapted to local realities rather than assumed to follow mainstream urban consumer models [64]. Some sensing modalities may also perform differently across populations or settings, and implementation burdens are not evenly distributed. Recent discussion in heart failure remote monitoring has made this especially clear by showing that sex- and race-based disparities may influence who benefits from digital follow-up and who is left behind [65]. Equity is therefore not a peripheral implementation issue. It is part of the core clinical question of whether digital monitoring improves care broadly or selectively.

Regulatory designation should not be inferred from the consumer platform alone. A single device may combine authorized medical-device functions with nonmedical wellness functions, while apparently similar devices may

Table 3. Common failure modes of wearable cardiovascular monitoring and their clinical implications.

Failure mode	Clinical presentation	Impact on care and management
False-positive rhythm alerts	Irregular rhythm notifications during artifact, ectopy, or non-AF arrhythmias.	Leads to unnecessary diagnostic testing, premature disease labeling, and low-yield escalation; underscores the need for established confirmatory pathways [7,38].
Data overload	Large volumes of patient-generated data received outside structured triage systems.	Increases administrative burden and reduces clinical value when incoming data are weakly validated, poorly prioritized, or non-actionable [1,6].
Anxiety and hypervigilance	Increased symptom preoccupation, repeated self-checking, and frequent unscheduled health-care utilization after wearable notifications.	Alters the patient's illness experience and may drive repeated, low-yield reassurance-seeking or downstream testing [60].
Overmedicalization	Interpreting normal physiological variation in heart rate, sleep, or recovery as pathological simply because it is visible.	Lowers the threshold for unnecessary intervention and expands disease language into ordinary daily life [3,6].
Actionability gap	Detection of physiological drift or deviation without a predefined clinical response pathway.	Erodes clinician confidence and produces "more data than care", especially when monitoring is disconnected from triage and management workflows [16,47].
Digital exclusion	Lower uptake or sustained use among older, lower-income, rural, or digitally less fluent populations.	Risks widening existing health-care disparities despite technological innovation [64,65].
Weak interoperability	Difficulty standardizing and integrating data across devices, platforms, and clinical systems.	Limits the scalability, reproducibility, and safety of remote monitoring workflows [1].

Abbreviations: AF, atrial fibrillation.

have different validation evidence, intended uses, and regulatory status. Clinicians should therefore consider the specific sensor, algorithm, software version, jurisdiction, and labeled indication when judging whether an output is sufficiently reliable for clinical use [23]. Regulation and interoperability are less visible to patients but just as important. Consumer platforms evolve quickly, hardware changes across product generations, and software updates may alter signal processing in ways that are opaque to users and clinicians. The AHA interoperability statement rightly emphasizes provenance, metadata, device versioning, and data portability [1]. Without better standards, even technically sound measurements may remain difficult to use consistently in clinical practice.

These practical weaknesses converge into several recurring clinical failure modes, as detailed in Table 3 (Ref. [1,3,6,7,16,38,47,60,64,65]).

A further limitation is conceptual. Continuous monitoring can make ordinary physiological variation look pathological simply because it has become visible. Heart rate fluctuates. Sleep varies. Ectopy occurs. Recovery is imperfect. Digital tools can enrich clinical understanding, but they can also erode tolerance for normal variability if every deviation is framed as a signal requiring response. This dynamic can contribute to overmedicalization. The solution is not to reject monitoring, but to retain clinical judgment about which abnormalities matter, in whom, and for what reason.

A related future direction is digital twin modeling, in which longitudinal physiological data, clinical risk factors, and disease-specific variables are used to represent an individual patient's cardiovascular state. In principle, this approach could bring wearable signals, electronic health records, imaging, genomics, and treatment response into a single patient-specific model. In current cardiovascular monitoring, however, digital twins remain mainly a research concept rather than a routine clinical tool. Their value will depend on transparent assumptions, external validation, and evidence that model-informed decisions improve outcomes rather than simply add another layer of computational complexity [66].

8. Conclusion

Digital cardiovascular medicine is clinically most persuasive when it is framed as a way of seeing cardiovascular abnormalities under the conditions in which they actually unfold. Wearables and related forms of digital monitoring do not derive their value from novelty alone. Their distinctive contribution is the ability to observe physiology repeatedly in daily life, to place abnormalities in relation to the individual's own recent baseline, and to examine disease while it is developing rather than only after it has become established. AF shows that this can already be useful when screening signals are linked to ECG confirmation and subsequent care. Heart failure, blood pressure behavior, sleep-related cardiovascular burden, and symptom interpretation suggest a wider horizon, though the evidence across these domains is less mature and less even. Progress will depend on distinguishing which patterns deserve trust, which require caution, and which should remain descriptive until

stronger evidence emerges. The next generation of prospective trials will need to determine not merely whether wearable signals can be generated, but which signals alter management, in whom, and with what effect on patient-centered outcomes. Equally important is whether health systems can integrate digitally acquired physiology into workflows that are clinically interpretable, selective, and proportionate. Health systems will also need tiered response standards for wearable-derived data, so that increasingly abundant signals do not simply translate into data overload, low-yield escalation, and clinician uncertainty. The field will have its greatest clinical impact if it improves understanding of abnormalities where they typically unfold—in daily life, early in their course, and within the individual's physiological background rather than only at the point of overt presentation.

Author Contributions

YW and ZZ contributed equally to this work and share first authorship. YW contributed to conceptualization, literature investigation, figure preparation, and writing of the original draft. ZZ contributed to conceptualization, clinical validation, critical revision of the manuscript, supervision, and project administration. WW contributed to literature investigation, evidence verification, and critical revision of the manuscript. All authors contributed to manuscript revision, read and approved the final version of the manuscript, and agree to be accountable for all aspects of the work.

Ethics Approval and Consent to Participate

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The authors declare no conflicts of interest.

Declaration of AI and AI-Assisted Technologies in the Writing Process

During the preparation and revision of this manuscript, the authors used AI-assisted tools to support language editing, wording refinement, and organization of the manuscript. The authors developed the scientific content, selected and verified the cited literature, critically reviewed and revised all AI-assisted outputs, and take full responsibility for the final content of the manuscript.

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