Digital Health and Remote Patient Monitoring in Heart Failure: From Pathophysiology to Value-Based Care in Emerging Health Systems

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Heart failure (HF) is one of the most complex, dynamic, and resource-intensive cardiovascular syndromes worldwide. It is associated with high morbidity, frequent hospitalizations, and substantial healthcare expenditures.[1] Despite major advances in pharmacological and device-based therapies, HF management remains largely reactive and symptom-driven rather than proactive. Moreover, adherence to guideline-directed therapy by both physicians and patients remains suboptimal.

Pathophysiological processes, including neurohormonal activation, often precede increases in intracardiac filling pressures and ultimately lead to congestion. Gradual alterations in autonomic tone may manifest as changes in heart rate, heart rate variability, blood pressure, sleep quality, and physical activity well before clinical deterioration becomes apparent. In addition, atrial fibrillation and malignant ventricular arrhythmias may occur abruptly in the setting of hemodynamic and autonomic stress.[2] Early detection of these physiological changes, prior to the onset of symptoms, could potentially prevent hospital admissions. However, current clinical practice remains predominantly symptom-driven and does not adequately reflect the dynamic biological progression of HF, resulting in delayed intervention and preventable decompensation.

HF is particularly well suited for longitudinal, physiology-driven surveillance. Accordingly, digital health technologies and remote patient monitoring (RPM) have emerged as promising strategies to identify early signs of deterioration—such as changes in hemodynamics, cardiac rhythm, autonomic balance, activity patterns, or patient-reported symptoms—and to enable timely intervention. When supported by adequate technical infrastructure and HF-trained healthcare professionals, these approaches may increase time spent at home and reduce HF-related hospitalizations.[3]

A growing body of evidence indicates that technology alone does not improve outcomes in HF; rather, clinical benefit depends on integrating remote monitoring into structured care pathways that clearly define responsibilities and enable proactive intervention. Earlier physician-led telemonitoring systems, such as Telemedical Interventional Monitoring in HF (TIM-HF), did not demonstrate a significant mortality benefit in ambulatory HF, highlighting the limitations of remote monitoring when workflow integration and response intensity are insufficient.[3] In contrast, TIM-HF2 incorporated daily transmission of home-based vital parameters and symptom assessments to a centralized telemedical center with predefined escalation pathways. This approach reduced the primary composite endpoint—days lost due to unplanned cardiovascular hospitalization or all-cause death—and was associated with lower all-cause mortality.[4]

Unlike earlier telemonitoring studies characterized by passive data transfer and heterogeneous clinical response pathways, TIM-HF2 evaluated a structured "remote patient management" model that combined daily physiological and symptom surveillance with a clearly accountable clinical process. Patients transmitted home-based measurements (e.g., body weight, blood pressure, and heart rate) along with standardized symptom and health status data to a central telemedical center staffed by trained healthcare professionals under physician supervision. The telemedical team systematically reviewed incoming data, contacted patients when alerts or concerning trends were identified, coordinated medication adjustments and care modifications with treating physicians, and escalated cases to HF specialists according to predefined criteria. In TIM-HF2, remote patient management significantly reduced the primary composite endpoint (percentage of days lost due to unplanned cardiovascular

hospitalization or all-cause death) compared with usual care. All-cause mortality was numerically lower (hazard ratio approximately 0.70), although cardiovascular mortality did not reach conventional statistical significance. These findings underscore a key principle: remote monitoring improves outcomes when embedded within an integrated, connected-care model in which continuous interaction between patients and healthcare professionals transforms physiological signals into timely, actionable therapeutic decisions. In contrast, deploying technology without a clearly defined response system is unlikely to yield meaningful clinical benefit.[4]

Among patients with limited digital literacy, regular telephone-based follow-up achieved outcomes comparable to—or in some cases better than—those observed with app-based system.[5] This observation further emphasizes the essential role of human interaction in digitally enabled care models.

Patients with implantable devices, including pacemakers, implantable cardioverter-defibrillators (ICDs), cardiac resynchronization therapy (CRT) devices, and pulmonary artery pressure (PAP) sensors, can benefit from high-resolution, device-based monitoring.

Invasive, device-based diagnostic techniques provide precise longitudinal data, enabling detailed correlations with HF pathophysiology, particularly congestion. Continuous monitoring of intracardiac or pulmonary pressures via implantable PAP sensors allows clinicians to adjust diuretic and vasodilator therapy—either escalating or de-escalating treatment—before overt symptoms arise. In the monitoring of PAP in patients with chronic-HF randomized trial, PAP-guided care significantly improved health-related quality of life and reduced HF hospitalizations compared with standard care in a contemporary European cohort.[6] Importantly, the benefit of structured monitoring is not limited to invasive devices. The fully published TIM-HF2 demonstrated that a structured remote patient management program, combining daily non-invasive home measurements (e.g., body weight, blood pressure, and heart rate) with standardized symptom and status assessments reviewed by a dedicated telemedical center with predefined escalation pathways, significantly reduced the primary composite endpoint (days lost due to unplanned cardiovascular hospitalization or all-cause death) and was associated with a lower all-cause mortality signal than usual care.[7] Collectively, these studies support a core principle: technology delivers clinical value only when integrated into a

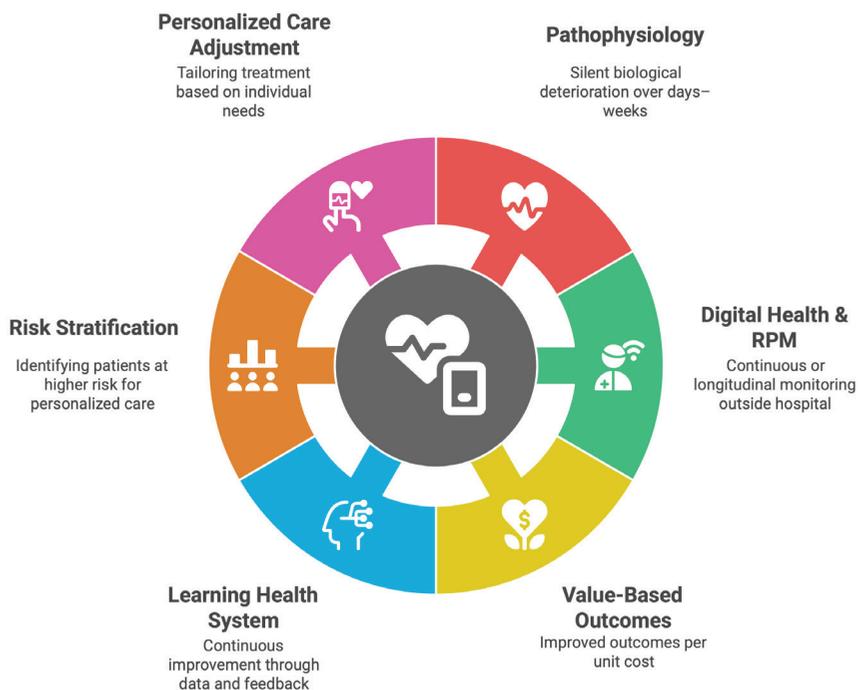## Digital Health in Heart Failure Management

FIG. 1. Digital health–enabled heart failure management framework. The schematic depicts how digital health and remote patient monitoring (RPM) translate heart failure pathophysiology into value-based care. Silent biological deterioration occurring over days to weeks (hemodynamic congestion, autonomic imbalance, arrhythmia risk) is documented through ongoing or longitudinal monitoring outside the hospital. Digital data integration facilitates risk stratification, personalized treatment adjustments, and connected care models that enable earlier intervention. This is an iterative process that leads to a learning health system in which clinical outcomes and healthcare efficiency are enhanced and value-based outcomes are maximized through reduced hospitalizations and improved resource use.

clear workflow that transforms physiological signals into timely therapeutic interventions and fosters sustained patient–clinician interaction.

Implanted electronic cardiac devices, including ICDs and CRT systems, also provide extensive diagnostic data on cardiac rhythm, physical activity, thoracic impedance, and autonomic tone. Detection of atrial fibrillation, ventricular arrhythmias, or device alerts necessitates timely clinical action to mitigate HF progression. When combined, these parameters can be monitored longitudinally to predict impending deterioration.[8] Effective utilization of these techniques relies on expert receiving centers, ideally employing interdisciplinary teams with expertise in both device management and HF care. These centers must maintain patient accessibility during the day and provide targeted therapeutic guidance.

For patients without implantable devices, PAP sensors, or deviceless remote monitoring. However, individual, single metrics are insufficient on their own; clinical utility depends on interpreting multiparametric data within a structured workflow and linking it to timely therapeutic interventions. Simple, cost-effective measures such as daily body weight, pulse, blood pressure, and symptom scores remain valuable. Remote consultations via platforms such as Teams or Zoom can further aid assessment of congestion through visual inspection, artificial intelligence (AI)–based voice analysis, and dyspnea scoring.

Wearable devices and smartphone cameras can be used for photoplethysmography (PPG) to estimate heart rate, detect irregular rhythms, evaluate peripheral perfusion, and assess surrogate markers of autonomic balance. Advanced camera-based PPG applications allow facial analysis without additional hardware, reducing barriers to participation and enhancing patient engagement. Bed– or smartphone–based ballistocardiography provides additional insights into cardiac mechanical activity and volume status. Voice-based biomarkers also offer a promising avenue; subtle changes in speech characteristics, vocal endurance, and respiratory modulation may indicate pulmonary congestion or fatigue before clinical symptoms are apparent.[9,10] Early data suggest that voice analysis may enable remote detection of HF worsening, providing a low-burden, patient-friendly signal that is particularly advantageous for elderly patients or those with limited digital literacy. These approaches may be especially relevant in middle-income countries or rural settings.[11] Importantly, some algorithms can also detect atrial fibrillation, a common trigger of decompensation and HF hospitalization.

Consequently, non-invasive, "deviceless" monitoring technologies are playing an increasingly important complementary role in the management of HF. A low-cost, multimodal strategy represents the near-future standard, while more sophisticated approaches to digital signal analysis are becoming progressively important for early detection and intervention.

Techniques in AI and machine learning can facilitate the integration of large numbers of heterogeneous physiological signals into individualized risk trajectories, enabling personalized

HF management. One promising paradigm is "management by exclusion," in which patients who remain within their unique physiological limits can be safely deprioritized, allowing clinical attention to focus on those who fall outside these limits. This approach is particularly advantageous in staff-limited settings.[12] Properly designed digital systems, rather than adding cognitive burden, can effectively triage risk, minimize clinician workload, and support proactive decision-making. Crucially, AI should function as a clinical decision-support tool while maintaining clinician oversight and accountability.

Evidence from both clinical trials and real-world implementations indicates that technology alone does not improve outcomes. Meaningful clinical benefit arises from integrating digital tools into connected-care models, where patient–healthcare professional interaction is timely, continuous, guided by defined escalation pathways, and grounded in shared decision-making. The human relationship remains essential: continuous communication, patient and family education, and trust are critical for engagement and adherence, particularly in chronic conditions such as HF (Figure 1).

The future of HF care lies in tailoring interventions to individual patients, delivered through variable intensity modalities rather than a single universal monitoring model. In low-resource settings, a practical initial approach is a cost-effective (RPM) template that incorporates widely available, non-invasive parameters such as daily body weight, blood pressure, heart rate/pulse, symptom scores, and systematic phone-based follow-up, with occasional video consultations when feasible. This model is scalable, suitable for elderly patients with limited digital literacy, and capable of detecting early signs of congestion or rhythm instability before hospitalization becomes necessary. Successful scaling of digital HF care in regions such as Eastern Europe, the Caucasus, and Central Asia requires prioritization of clinician and HF nurse training, clear escalation pathways, and integration of (RPM) into routine workflows rather than operating as parallel "technology-only" processes. Ideally, a pragmatic randomized controlled trial comparing this simplified remote monitoring approach with standard episodic care should be conducted, with outcomes aligned with value-based healthcare metrics, including HF hospitalizations, total bed days, quality of life, and cost-effectiveness. From a policy perspective, this strategy targets the primary cost driver in HF—hospital admissions—by shifting care upstream from reactive inpatient rescue to proactive HF prevention. Ultimately, digital health should be viewed not as an expensive technological tool, but as a scalable, connected-care method capable of enhancing quality and efficiency in short-staffed or rural settings, while preserving the fundamental human elements of continuous dialogue and shared decision-making.

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