Int J Heart Fail. 2021 Jan;3(1):31-50
https://doi.org/10.36628/ijhf.2020.0023
pISSN 2636-154X·eISSN 2636-1558

International Journal of Heart Failure
IJHF

Review Article

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Remote Patient Monitoring in Heart Failure: Factors for Clinical Efficacy

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OPEN ACCESS

Received: Jun 30, 2020
Revised: Oct 19, 2020
Accepted: Nov 6, 2020

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Conflict of Interest
Ankit Bhatia has no financial conflicts of interest. Dr. Maddox discloses current grant funding from the NIH NCATS (1U24TR002306-01: A National Center for Digital Health Informatics Innovation), current consulting for Creative Educational Concepts, Inc. and Atheneum Partners, and honoraria and/or expense reimbursement in the past 3 years from the University of Utah (May 2017), New York Presbyterian (Sept 2017), Westchester Medical Center (Oct 2017), Sentara Heart Hospital (Dec 2018), the Henry Ford health system (March 2019), and the

ABSTRACT

Despite clinical advances in its treatment, heart failure (HF) is associated with significant adverse clinical outcomes and is among the greatest drivers of healthcare utilization. Outpatient management of HF remains suboptimal, with gaps in the provision of evidence-based therapies, and difficulties in predicting and managing clinical decompensation. Remote patient monitoring (RPM) has the potential to address these issues, and thus has been of increasing interest to HF clinicians and health systems. Economic incentives, including increasing RPM reimbursement and HF readmission penalties, are also spurring increased interest in RPM. This review establishes a framework for evaluating RPM based on its various components: 1) patient data collection, 2) data transmission, analysis, and presentation, and 3) care team review and clinical action. The existing evidence regarding RPM in HF management is also reviewed. Based on the data, we identify RPM features associated with clinical efficacy and describe emerging digital tools that have the promise of addressing current needs.

Keywords: Heart failure; Telemedicine

BACKGROUND

The global burden of heart failure (HF) continues to rise, affecting at last 26 million people as of the leading causes of morbidity and mortality globally.[1-3] This population is expected to increase by 50% by 2030, placing an increasing burden on the global healthcare system and highlighting the need for innovations in HF care.[4]

HF management also carries significant economic implications. While difficult to estimate globally, direct medical costs of HF care continue to rise as prevalence increases. In the US, $30.7 billion was spent on HF care in 2012, which is estimated to double by 2030. In many countries, quality programs have shifted the HF economic burden onto health systems, such as through the US's Hospital Readmissions Reduction Program (HRRP), with HF readmissions the main contributor to Medicare reimbursement reductions.[5-7] Given these clinical and economic motivations, and the shortcomings of current strategies, significant efforts have been devoted to developing more effective HF management approaches.

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Author Contributions

Conceptualization: Bhatia A; Data curation: Bhatia A; Supervision: Maddox T; Writing - original draft: Bhatia A; Writing - review & editing: Maddox T.

Optimal HF care relies on several components for effective overall management. First is the provision of guideline-directed medical therapies. Several pharmacotherapies have demonstrated mortality benefit in HF patients, specifically in those with reduced ejection fraction.[8)9)] However, consistent provision of these therapies, at optimal dosing, does not occur.[10)] A contributor to this gap is the logistical challenges of administering these medications. For example, most HF medications require stepwise titration of doses to ensure tolerability, which often only occur at clinic visits. This results in delays in medication titration and inconvenience for patients.

Second is effective surveillance for disease progression. Outpatient HF management requires ongoing vigilance for indications and symptoms of congestion. Failure to detect and manage these symptoms can result in emergency room (ER) visits and hospitalizations. Although many patients and care teams attempt to monitor their condition with techniques such as daily weight measurement and blood pressure (BP) monitoring, the burden on patients to collect this data and difficulties delivering this information to care teams in a timely and actionable manner complicate this approach.[11)] As a result, these approaches have not demonstrated consistent clinical efficacy.

Remote patient monitoring (RPM) aims to address these gaps in current HF care. RPM is a strategy that allows care teams to monitor and manage patients outside of traditional healthcare encounters. This approach has the capabilities to further optimize HF medical care by permitting more complete and timely delivery of guideline-directed medical therapy (GDMT), and enhance monitoring for clinical decompensation.

RPM can occur by a variety of approaches. One approach involves using an implantable biometric sensor to monitor HF status, such as intracardiac pressure measurements via hemodynamic sensors (e.g., CardioMEMS) or intrathoracic impedance assessments via cardiac implantable electronic devices (CIEDs).[12)] Other approaches use biometric sensors that sit outside of the body, such as BP cuffs, scales, and wearable biosensors.

RPM strategies employing invasive biosensors have demonstrated significant reductions in HF admissions.[12)13)] However the benefits of invasive RPM must be weighed against the risks of implanting an invasive device and associated cost.[14)] These tradeoffs were highlighted in a 2017 Heart Failure Society of American (HFSA) consensus statement on invasive biometric sensing. It concluded that they "may be beneficial in selected patients or when used in structured programs, but the value of these devices in routine care requires further study."[15)]

By contrast, RPM strategies that use noninvasive biometric sensors have minimal risk and are generally less expensive than invasive devices. As such, they can be applied to a greater proportion of the HF population. However, evidence supporting their clinical benefit is mixed. The 2017 HFSA consensus statement on RPM strategies using noninvasive biometric sensing acknowledged their weak evidence base, and stated that further research was required to effectively evaluate associated outcomes.[15)]

Today, the field of RPM continues to evolve and is being incorporated into cardiology practice. Advances in data collection, monitoring, analysis, and clinical workflows all have the potential to improve the effectiveness of RPM strategies, especially those relying on noninvasive biometric sensing. Furthermore, the regulatory environment, including reimbursement for RPM activities and penalties for HF readmissions, further incentivizing such advances. Additionally, shifting practice patterns due to COVID-19 have led to a further

push to manage patients outside the traditional office setting. However, rigorous evaluation of these emerging RPM advances will be necessary to demonstrate their clinical efficacy.

Below, we overview RPM and its various components. We then review the current evidence supporting RPM strategies in HF management, and highlight emerging RPM tools and strategies. Based on the evidence, we identify RPM features associated with clinical efficacy and discuss how emerging tools may help to address current needs.

RPM

Mechanistic reasoning

Traditional strategies for avoiding HF hospitalizations have largely relied on patient detection of congestive symptoms and care team assessment of volume status. Many of these strategies have been found to be relatively ineffective in avoiding ER visits or hospitalizations.[16] This is partly because congestive symptoms lag behind the initial rise in intracardiac pressures, prompting a "reactive" management strategy.[17][18] Furthermore, care teams can generally only assess for signs of congestion in healthcare settings, rather than a patient's home.

Intracardiac pressures have been shown to rise up to 20 days prior to onset of congestive symptoms in HF patients, and serve as the earliest physiologic indicator for decompensation.[19] In addition to intracardiac pressures, symptomatic decompensation is typically preceded by numerous other downstream physiologic and subclinical indicators, including activity reduction and changes in respiratory rate.[20] The goal of RPM in HF is to identify preclinical indications of decompensated HF and proactively prompt clinical management changes. This would potentially reduce patient morbidity and avoidable acute medical encounters.

What is remote patient monitoring?

RPM is a strategy that allows care teams to monitor and manage patients outside of traditional healthcare encounters. Broadly, RPM includes methods for: 1) patient data collection, 2) data transmission, analysis, and presentation to the care team, and 3) clinical review and action in response to the RPM information. **Figure 1** outlines this general schematic. In practice, there

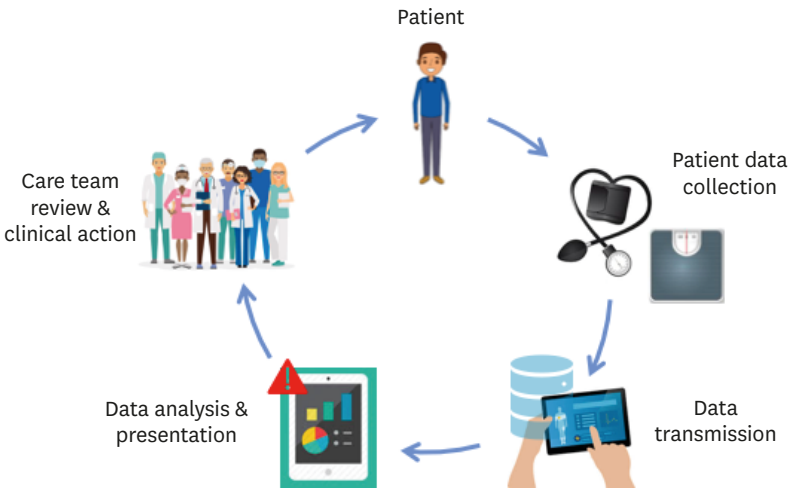

Figure 1. Remote patient monitoring schematic.

https://doi.org/10.36628/ijhf.2020.0023

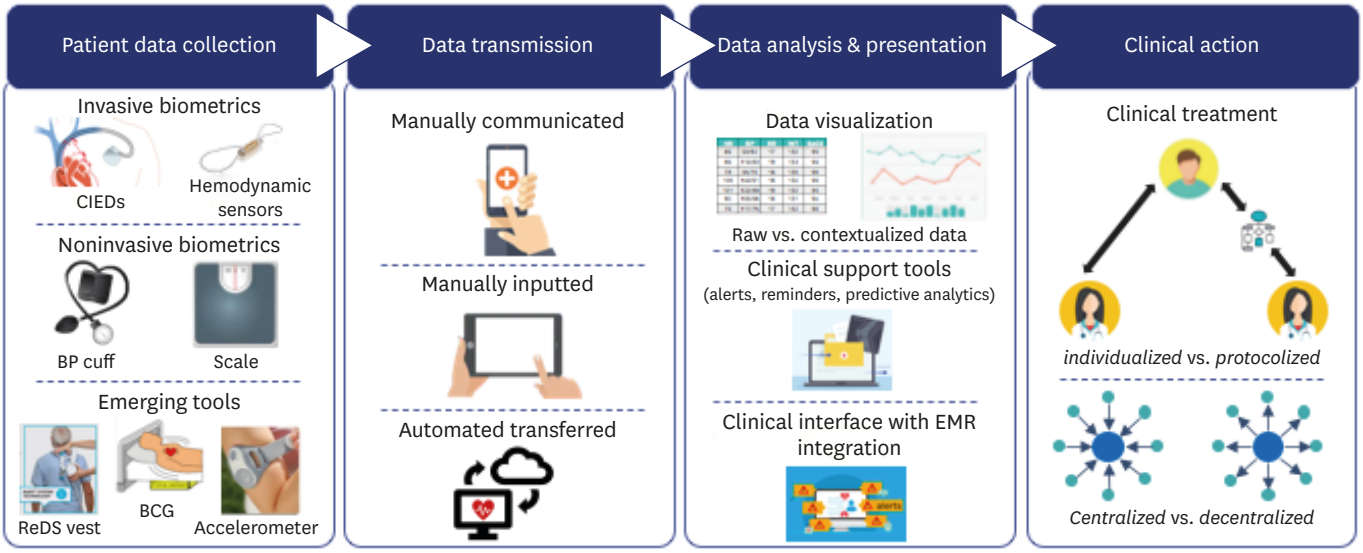

Figure 2. Remote patient monitoring components with associated strategies.[21)22)]

are a variety of approaches for conducting RPM. **Figure 2** outlines the various strategies for each component of RPM, as are subsequently described below.

Patient data collection

A variety of data elements can be collected by RPM strategies. Broad patient data categories include: 1) invasive biometric data (e.g., pulmonary artery (PA) pressures, intrathoracic impedance), 2) noninvasive biometric data (e.g., BP, weight, and pulse oximetry), and 3) symptom assessments.

Invasive biometrics

RPM strategies that use invasive biometric sensing involve implantation of an indwelling device for continuous monitoring and data collection. The two main approaches with widespread clinical use are implantable hemodynamic monitors and CIEDs. **Figure 3** outlines the workflow for each of these invasive approaches, as outlined below.

Hemodynamic monitors

Among implantable hemodynamic monitors, several had previously been tested including a right ventricular pressure sensor and a left atrial pressure sensor.[23)24)] However, neither

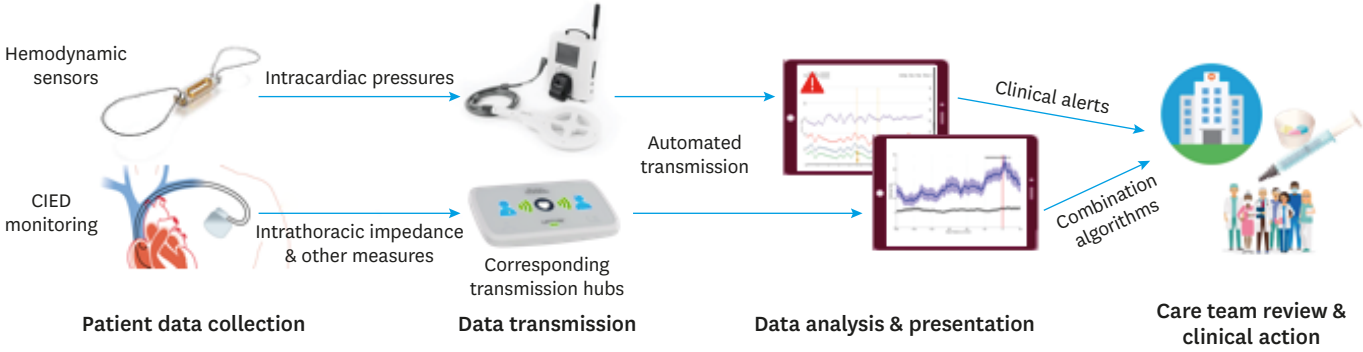

Figure 3. Remote patient monitoring workflow employing invasive biometric sensors.[27)29)]

https://doi.org/10.36628/ijhf.2020.0023

received market approval due to procedural complications and sensor failure. In contrast, CardioMEMS, a wireless implantable PA hemodynamic sensor, has gained prominence as a primary invasive hemodynamic monitoring strategy.[12] Measurements are automatically taken by the sensor, and then transferred to the care team using a home unit for daily sensor interrogation. Elevated PA pressures above patient-defined thresholds serve as an early indicator of clinical decompensation.[25]

CIEDs

CIEDs can capture numerous types of invasive biometric data, including heart rate (HR), respiratory rate (RR), and HR variability. Many also have capabilities for detecting and treating tachyarrhythmias, and identifying atrial arrhythmias. CIED data typically is automatically collected and transmitted to the care team using a corresponding home transmission hub.

Among these CIED measures, intrathoracic impedance, a reflection of thoracic fluid content, has demonstrated the greatest promise for HF clinical decompensation prediction. It is calculated by the electrical impedance between the device box and the defibrillation electrode located in the right ventricle.[19] Repeated impedance measurements are subsequently used to derive clinically-meaningful thresholds, indicating HF decompensation.[26] Many CIEDs also now employ multifactorial algorithms combining intrathoracic impedance with other biometrics to alert for HF clinical decompensation.[27][28]

Noninvasive biometrics

Unlike invasive biometric sensing paired with automatic data collection, noninvasive approaches to biometric sensing can be either active or passive. *Active approaches* require patients to manually obtain data (e.g., stepping on a scale to obtain weight). *Passive approaches* obtain data without a required patient action (e.g., bed sensor that automatically measures RR while patient sleeps).

Many RPM programs provide patients tools to collect standard biometrics, as would be collected in a traditional office visit. These include: sphygmomanometer (BP), scale (weight), and pulse-oximeter (oxygen saturation, HR). Some programs will also include cardiology-specific tools, including electrocardiogram (ECG) portable devices.

Emerging data collection tools

While currently not being routinely deployed in RPM programs, emerging tools for obtaining patient data will likely see future incorporation. Among the most promising are ambient biosensors: external devices that passively capture biometric data.[30] These include "wearables," sensors externally applied directly to the body, or other sensors in the home that can measure biometrics.[31] Examples of emerging digital health tools include: 1) Wearable accelerometers for activity level and step-count tracking.[32][33] 2) Remote Dielectric Sensing (ReDS) system wearable vest to monitor intrathoracic fluid content.[34] 3) Passive under-bed sensors that assess heart and lung movement to derive HR, RR, and other physiologic parameters.[35][36]

Data transmission, analysis, and presentation

Once patient data has been collected, it is then transmitted to care teams either by direct communication by the patient or electronically. To facilitate this, many RPM programs use mobile devices (mobile phone, tablet) to serve as a home hub, interconnected with other data collection devices to automatically aggregate and transmit patient data.

https://doi.org/10.36628/ijhf.2020.0023

Following transmission, patient data is then presented to the care team. The simplest process for this is having all raw patient data directly displayed and reviewed by the care team. However, this often presents significant clinical workflow challenges, given the substantial time requirements to interpret this raw data. Accordingly, more advanced data presentation approaches have been developed, including visualizing patient data longitudinally to assess trends, and with associated contextual information (e.g., healthcare encounters, medication changes). Many interfaces for patient data review are also now integrated into the electronic medical record (EMR) to reduce duplicative workflows.

In addition, many RPM programs incorporate "alerts" when patient data falls outside predefined parameters (e.g., BP below normally-defined range). These alerts can be prioritized based on degree of severity. Some RPM programs (including CIED monitoring) also apply algorithms, assessing multiple data streams and alerting clinicians when risk prediction crosses defined thresholds.

Another RPM feature of growing interest is the use of artificial intelligence and predictive-analytics capabilities to aid as clinical decision support tools. While these features remain in relatively early development, they reveal future promise as RPM platforms continue to gather patient-level biometric and outcome data. The use of predictive analytics for clinical decision support remains primarily confined to risk assessment: assessing multiple data streams and alerting clinicians when decompensation risk crosses defined thresholds. Clinical decision support tools can also aid in automation of HF treatment protocols (e.g., doubling loop diuretic for specific weight thresholds).

Care team review and clinical action

RPM clinical data review and associated workflow structure can vary significantly.

Clinical data review can be either via *centralized monitoring*, reviewed by a singular clinical entity, or *decentralized monitoring*, reviewed by individual providers or practices. Among centralized monitoring centers, some are also directly responsible for patient management (*centralized management*) while others defer management to a patient's corresponding clinician. Clinical monitoring practices include continuous monitoring (24/7) versus monitoring during standard work hours. Once clinical action is deemed necessary, then it can be delivered, either via pre-specified clinical algorithms (*protocolized*) or tailored to the individual patient (*individualized*).

EVIDENCE SUPPORTING RPM

A variety of studies have evaluated the impact of RPM strategies on patient outcomes. These include studies focused on both RPM approaches using invasive and noninvasive biometric sensing.

When reviewing RPM randomized control trials, a methodologic limitation to consider is the difficulty to effectively double-blind study participants. While many trials provided monitoring technologies or even invasive procedures to control group patients in an attempt to minimize placebo and Hawthorne effects, the associated data feedback loop often makes it difficult to blind patients and clinicians.[37] This in turn may overestimate the impact of RPM in these studies.

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Hemodynamic monitors

Regarding hemodynamics monitors, several have been developed including intracardiac and PA pressure sensors. Initial studies of a right ventricular pressure sensor and left atrial pressure sensor were not successful.[23][24] The right ventricular pressure sensor was studied in the COMPASS-HF trial, which revealed a trend towards reduction in composite HF admissions, ED visits, and urgent clinic visits, however an expanded trial was stopped due to sensor failure.[23] The Heart Pod, a left atrial pressure sensor, demonstrated a reduction in HF hospitalizations, however the trial was halted prematurely due to implant-related transseptal complications, requiring pericardiocentesis or surgical management.[24]

In contrast, CardioMEMS (Abbott, Atlanta, GA, USA), a wireless implantable PA sensor, has gained prominence as a primary invasive hemodynamic monitoring strategy.[12] The CHAMPION Trial (CardioMEMS Heart Sensor Allows Monitoring of Pressure to Improve Outcomes in NYHA Class III Heart Failure Patients trial) assessed the use of CardioMEMS in 550 (494 with reduced systolic function) patients with HF with a recent HF hospitalization over 6 months.[25] All patients underwent CardioMEMS implantation, and were then randomized to PA-pressure guided HF management strategy arm versus a control group receiving standard-of-care. The protocol defined a treatment goal to lower elevated PA pressures using neurohormonal, diuretic, or vasodilator therapy. The primary efficacy endpoint was HF-related hospitalizations following implantation in the treatment group versus the control group.

CardioMEMS use was associated with a 37% reduction in HF hospitalizations at 6 months, with improved quality-of-life assessments.[12][25] A post-approval "real-world" study revealed a similar reduction in HF hospitalizations.[38] In CHAMPION, the monitored group also had a significantly greater number of HF medication changes overall. This included a significant increase in doses of GDMT angiotensin-converting enzyme (ACE) inhibitors/angiotensin receptor blockers (ARBs) and beta blocker doses over the 6-month duration of the study, which was not observed in the control group.[39]

In CHAMPION, patient adherence to daily transmissions had a median 88% daily compliance and 100% weekly compliance (defined as at least one transmission in a 7-day period). A large follow-up practice-based study also revealed high adherence to daily transmissions (98.6% median adherence in 2000 patients with average follow-up time 333 days).[40] There was a non-significant dropoff in patient adherence that was observed after the initial implantation period (days between transmissions ranged from 1.1 days in the first 30 days to 1.3 days after 6 months).[40]

To date, CardioMEMS is the only available invasive biometric sensor that has demonstrated a reduction in HF events. Further CardioMEMS study is currently being conducted with the Hemodynamic-GUIDEd Management of Heart Failure (GUIDE-HF) trial, which will examine symptomatic HF patients regardless of EF, with primary composite endpoint that will include HF hospitalizations, mortality, and medical evaluations requiring intravenous diuretic therapy.[41]

CIEDs

CIEDs capabilities, specifically intrathoracic impedance measurement and subsequent multifactorial algorithms, have also been evaluated for HF RPM.

https://doi.org/10.36628/ijhf.2020.0023

The Diagnostic Outcome Trial in Heart Failure (DOT-HF) trial examined the performance of intrathoracic impedance monitoring via the OptiVol fluid monitoring algorithm (Medtronic, Fridley, MN, USA) to predict HF events.[42] 345 HF patients with recently implanted CIEDs were enrolled, randomized to either have OptiVol alert enabled versus not for a follow up 14.9±5.4 months. Patients in the alert arm were noted to have a greater number of hospitalizations (HR=1.79, p=0.02) and office visits (250 vs. 84; p<0.01). OptiVol alerts were noted to have a low 62% sensitivity for HF hospitalizations. Alerts also had a high false positive rate; of 144 alerts triggering office visits, 114 (79.2%) did not have signs/symptoms of cardiac decompensation. The SENSE-HF trial (Sensitivity and positive predictive value (PPV) of implantable intrathoracic impedance monitoring as a predictor of HF hospitalizations) revealed similar findings evaluating Optivol intrathoracic impedance monitoring in HF patients; among 210 patients with an OptiVol alert that were evaluated within 30 days, 80 had worsened HF status (PPV=38.1%, sensitivity 42%).[43]

Thus, despite its initial promise, intrathoracic impedance monitoring as a sole measure demonstrated poor sensitivity and specificity for clinical HF decompensation. In fact, the use of this measure appears to have resulted in more HF hospitalizations and outpatient visits.

Algorithms employing intrathoracic impedance in combination with other clinical parameters have demonstrated enhanced predictive power. The MultiSENSE (Multisensor Chronic Evaluation in Ambulatory Heart Failure Patients) trial similarly evaluated the combination algorithm HeartLogic (Boston Scientific, St. Paul, MN, USA) in CRT-D patients to predict worsening HF.[27][28] HeartLogic combined variables found to be independent predictors of HF events, including intrathoracic impedance, RR, HR, heart sounds, and activity level, to develop a composite HeartLogic index value. This index value was updated daily based on changes from the patient's baseline, with alerts generated when the value crossed a defined threshold. The algorithm was validated in 400 HF patients over a median of 322 days. The study revealed an above-goal sensitivity (70%) of predicting HF events with a median alert window of 34 days, while minimizing unexplained alerts (1.47 per patient-year). Several other trials have also demonstrated the augmented HF predictive capacity of CIED-based combination algorithms.[44][45]

While combined algorithms have demonstrated the ability to identify HF patients at risk for decompensation, data regarding these algorithms' effects on HF outcomes remains unclear.[46] The Multiple Cardiac Sensors for the Management of Heart Failure (MANAGE-HF), a randomized multicenter clinical trial currently enrolling, aims to assess HF RPM employing the HeartLogic algorithm with the composite endpoint of all-cause mortality and HF hospitalizations.[47]

Structured telephonic support

The Telemonitoring in Patients with Heart Failure (Tele-HF) study was a multicenter randomized study of 1653 HF patients (70% HFrEF) discharged from a HF hospitalization in the last 30 days. Patients were randomized to a telephone-based interactive voice-response system that collected daily information about symptoms and weight, versus usual care. Information was downloaded daily and reviewed every weekday by the clinical team. No difference was observed in the primary endpoints HF hospitalizations or mortality at 180 days.[48] The study was notable for high rates of nonadherence in the telemonitoring group: 14% of patients who were randomly assigned to undergo telemonitoring never used the system. Among those that used the intervention, adherence decayed during the study, with 90% using the system at least 3 times weekly at week 1 and only 55% using the system at

week 26. Significant resources were devoted to promoting patient engagement, including automated and personalized follow up calls.

The Better Effectiveness After Transition–Heart Failure (BEAT-HF) randomized multicenter trial had a similar design, with patients randomized to intervention of combined health-coaching telephone calls and remote monitoring following HF hospitalizations.[49] The study revealed no difference in HF hospitalizations or mortality.[49] Nonadherence was again thought to play a role in study findings, with only 55% adherent to remote monitoring at 30 days and 52% at 180 days. 17% never used remote monitoring equipment.[49-51]

Non-invasive biometric assessment

The Telemedical Interventional Monitoring in Heart Failure (TIM-HF) study, a randomized multicenter trial of 710 stable ambulatory HF patients assigned to telemedical management versus usual care, yielded similar findings.[50-52] Recruited patients were NYHA Class II-III with LVEF <25%, or LVEF ≤35% with a history of HF hospitalization or intravenous diuretic use in the last 2 years. Patients were randomized to a telemedical intervention that included a portable ECG device, BP cuff, and scale connected via Bluetooth to a personal digital assistant that subsequently sent automated encrypted transmission to the telemedical centers. All patients were managed at 2 telemedical centers with physician-led medical support 24 hours per day, 7 days per week for the study period. Patients were followed for a median 26 months. No significant change was noted in all-cause mortality (8.4% vs. 8.7%, HR=0.97) or hospitalizations (14.7 vs. 16.5 incidence per 100 patient-years at risk, HR=0.89). The study was notable for high adherence for the full duration of the study: 287 (81%) of 354 patients assigned to telemonitoring were at least 70% compliant with the daily transfer of data to the telemedicine centers.

While TIM-HF had similar outcomes to Tele-HF, TIM-HF was notable for significantly improved patient adherence to telemonitoring and had a more robust telemonitoring intervention with 24/7 patient contact and monitoring. TIM-HF's stable ambulatory HF population and low event rate was thought to be a contributor to the neutral result. Exploratory subgroup analysis revealed a reduction in days lost due to HF admission among patients in the intervention arm with a history of decompensation in the past two years.[52]

The follow up Telemedical Interventional Management in Heart Failure II (TIM-HF2) took a similar approach, this time with a more defined patient population.[53] This multicenter trial recruited 1,571 patients, randomized to RPM versus usual care. RPM again consisted of daily transmission of weight, BP, HR, ECG, and pulse oximetry via Bluetooth-enabled devices with automated transfer to telemedical centers with physician-led medical support and patient management with 24/7 coverage. Patients were NYHA class II-III with a HF hospitalization in the last 12 months with LVEF <45%, and were followed for 12 months. 743 of 765 (97%) were at least 70% compliant with the daily transfer of data to the telemedical center, with all patients contacted within 24 hours of missing data transmissions. Patients receiving RPM had a lower percentage of days lost due to unplanned cardiovascular (CV) hospital admissions or all-cause death versus usual care (4.88% vs. 6.64%, HR=0.80, p=0.046). All-cause mortality was also reduced in the RPM group (7.9% vs. 11.3% per 100 person-years, HR=0.70, p=0.028). HF hospitalizations were not analyzed as an independent endpoint.[53]

RPM's demonstrated efficacy in TIM-HF2, despite a shorter study period, may be attributed to a more narrowly-defined patient population with higher event rate, and proactive management strategy based on patient risk assessments.

Beyond multicenter clinical trials, there have been numerous single-center experiences evaluating RPM, both partnering with external vendors and with internally-designed RPM platforms. Mount Sinai Health System internally designed a digital RPM platform, RxUniverse, which was prospectively studied for post-discharge HF management. RPM was conducted using a mobile application and Bluetooth-enabled smart devices (BP cuff and digital scale).[54] Data was subsequently transmitted to the clinical team, with alerts for vital sign abnormalities. Among the 58 patients enrolled in the pilot, 30-day readmission rate was noted to be significantly lower at 10% than hospital readmission rates (23%) and national averages. Among the 58 patients, adherence to data transmission dropped from 83% in the first week after discharge to 46% in the fourth week.

Similar prospective trials evaluating the efficacy of RPM in HF management, both with internally-developed and commercial platforms, are currently being conducted that will further expand the evidence base.

Emerging biometric data collection tools

Several emerging data collection tools, namely ambient biosensors, show promise to potentially address non-adherence issues seen in prior ambulatory RPM studies. Ambient biosensors rely on passive collection of biometric data, rather than requiring a patient to take action to collect and report data.

The Multisensor Non-invasive Remote Monitoring for Prediction of Heart Failure Exacerbation (LINK-HF) Study examined the performance of a multisensor patch placed on the chest to predict HF rehospitalizations.[55] 100 HF patients were enrolled at time of hospital discharge and followed for up to three months. The multisensor patch consisted of a skin sensor and accelerometer to derive HR, RR, arrhythmia burden, gross activity, sleep, and posture. Data was then uploaded to a cloud analytics platform (PhysIQ, Chicago, IL, USA), with dynamic deviations from patient baseline values used to calculate the Multivariate Change Index (MCI) score. The MCI score was then retrospectively validated and found to have a 76–88% sensitivity and 85% specificity based on 35 total unplanned hospitalizations. Median time between initial alert and readmission was 6.5 days. Adherence was noted to be high, with 87 of the 100 patients completing the minimum 30 days monitoring.

Stand-alone accelerometers/activity trackers, used as a surrogate of daily activity level, have also been studied in HF patients. These include the SenseWear Pro3 Armband (BodyMedia, Inc., Pittsburgh, PA, USA), which was studied in 68 HF patients for 48 hours to assess daily physical activity. The accelerometer demonstrated high transmission fidelity, with activity level results consistent with corresponding NYHA Class.[56]

Accelerometers are also now included as part of the Apple Watch (Apple, Cupertino, CA, USA), which primarily thus far have been studied for their use of plethysmography to diagnose atrial fibrillation.[57] Smart watches also possess further potential to be employed in HF management, with demonstrated ability to obtain wrist BPs.[58]

Another emerging tool in HF management is the ReDS vest (Sensible Medical Innovations Ltd., Netanya, Israel), which employs wearable anterior and posterior sensors utilizing radar technology to measure the dielectric properties of lung tissue and assess relative lung fluid content. The device was studied in 50 patients following a HF hospitalization, with ReDS-guided management for 90-days following discharge. Compared to the 90 days prior

to enrollment, ReDS-guided management patients had a significant 87% reduction in HF hospitalizations (HR=0.07, p=0.01).[34]

The ballistocardiogram (BCG) has represented another promising tool; it is a passive sensor which can take multiple forms (wearable patch, under-bed sensor, toilet seat sensor) measuring ballistic forces related to heart and lung movement. It subsequently uses this data to derive HR, RR, and other associated physiologic parameters. Several small studies employing BCG data-derived algorithms have demonstrated the ability to effectively classify compensated versus decompensated disease states in HF.[35][36][59]

Similarly, wearable ring-based sensors have shown the ability to obtain beat-to-beat pulse pressure palmar artery volumes. These technologies, combined with emerging pulse-contour analysis to calculate cardiac output, have potential applicability in HF given variance based on disease status.[60][61]

FACTORS FOR EFFECTIVE RPM

As outlined in the evidence above, there is a clear chasm in RPM clinical efficacy between invasive and noninvasive approaches to biometric sensing. However, while the majority of RPM trials employing noninvasive strategies have yielded neutral results, select trials did demonstrate meaningful reductions in HF hospitalizations.[53] As the field of RPM continues to evolve with the incorporation of emerging tools, what can the evidence teach us about the factors required for effective RPM? **Table 1** summarizes the necessary factors and key actions for effective RPM as described below.

Table 1. Considerations for effective remote patient monitoring

Factors	Key actions	Considerations
Patient data collection	Optimizing patient selection	• Select patients at high enough risk for decompensation • Stable ambulatory and end-stage HF patients less likely to benefit
	Monitoring indicators of preclinical decompensation	• Ensure that monitored patient biometrics, either individually or in combination, have demonstrated predictive power for clinical decompensation • Leverage existing patient data via predictive analytics and combination algorithms to identify early clinical decompensation
	Enhancing patient adherence	• Minimize patient-driven data collection tasks • Promote passive strategies for data collection and transmission, such as the use of ambient biosensors
Data transmission, analysis & presentation	Optimizing clinical alerts	• Optimize alerts to match clinical review capabilities • Maximize alert "signal-to-noise ratio" to direct clinicians to review clinically-actionable data • Minimize false positives that may result in unnecessary healthcare encounters
	Ensuring privacy and security	• RPM technologies often exempted from medical device regulation and federal patient data privacy mandates • Ensure appropriate vetting of RPM technologies for cybersecurity safeguards and patient data protection
Care team review & clinical action	Standardized management strategies	• Define and standardize clinical management strategies in response to alerts
	Guideline-directed medical therapy titration	• Incorporate uptitration to maximally-tolerated doses of GDMT as part of RPM-based management strategies
	Centralized and timely monitoring and management	• Minimize the lag time between clinical alert and management change
	Promoting clinical adoption/buy-in	• Ensure RPM integration into existing clinical workflows, including EMR • Minimize RPM-related duplicative work
	Deriving cost effectiveness	• Given lack of direct cost effectiveness comparison data, must be assessed at the per-patient and per-RPM strategy level

EMR = electronic medical record, GDMT = guideline-directed medical therapy, HF = heart failure, RPM = remote patient monitoring.

https://doi.org/10.36628/ijhf.2020.0023

Patient data collection

Optimizing patient selection

RPM is neither necessary nor beneficial for every patient with HF. In fact, RPM can only be successful if the patient population has a high enough clinical event rate to allow for meaningful reduction and prevention. This is clearly seen when reconciling the discordant findings observed in the TIM-HF and TIM-HF2 trials.[50)53)] Both trials had similar design, clinical management, and included NYHA class II-III patients. However, TIM-HF's broader inclusion criteria translated into a smaller proportion of patients with a HF hospitalization in the past year. As a result, the TIM-HF patient population had a significantly lower observed HF hospitalization rate, with no difference observed between RPM and control arms despite high patient adherence. On the other hand, TIM-HF2's inclusion criteria required a HF hospitalization in the last year. As a result, TIM-HF2 had a higher event rate, and demonstrated reduction in percentage of days lost due to CV hospital admission or all-cause death. A similar higher event rate was observed in the CHAMPION trial evaluating CardioMEMS, with recent hospitalization part of the inclusion criteria. Taken together, this suggests that RPM strategies are most effective for patient populations at high risk for HF decompensation, such as those recently hospitalized.

Monitoring indicators of preclinical decompensation

It is well established that a rise in intracardiac filling pressures precedes onset of congestive HF symptoms.[17)18)] This direct relationship is the basis for CardioMEMS' effective PA hemodynamic monitoring and management strategy.[25)]

Along the same pathway, following a rise in filling pressures, other physiologic indicators including intrathoracic impedance have also been shown to precede clinical decompensation. Given the closer temporal correlation to decompensation onset, these indicators have demonstrated lower predictive power versus intracardiac filling pressures.[20)] Through use of predictive algorithms to analyze multiple physiologic indicators of decompensation including intrathoracic impedance, CIEDs have also demonstrated the ability to predict future 30-day HF events.[44)]

RPM approaches that rely on noninvasive monitoring of biometric data (e.g., HR, weight, etc.), are limited to indirect assessment of volume and hemodynamic status. Interpreting in isolation, these measures do not have significant predictive power for decompensation and serve more as indicators for current signs of decompensation. However, several noninvasive approaches using either earlier indicators of decompensation (e.g., intrathoracic impedance) or integrating a variety of biometric data (e.g., multisensor patches that detect HR, RR, etc.) have now demonstrated predictive power; this list of noninvasive tools will likely continue to grow.[34)55)] A further push is required to further identify noninvasive predictors of decompensation, and employ predictive analytics to better leverage existing data.

Enhancing patient adherence

RPM can only be successful if there is, in fact, patient data to monitor. RPM strategies using invasive biometric monitoring employ, by definition, a passive approach to patient data collection, and high adherence rates have been observed in CardioMEMS and CIED RPM studies.[25)27)28)] By comparison, RPM approaches using non-invasive biometric sensing have demonstrated substantially lower patient adherence.[27)28)] This low adherence to data collection likely factored into these studies' neutral outcomes.[48)50)62)] In these trials, nonadherence generally fell into two categories: patients never transmitting data (observed

in up to 20% of enrolled patients)[49] and decay in patient adherence over time (90% adherent at 1 week, 55% adherent at 6 months in Tele-HF).[48] Furthermore, among the studies of non-invasive biometric sensing demonstrating clinical efficacy, higher patient adherence to data collection and transmission was observed.[45][53]

Some factors affecting patient adherence in RPM programs include: ease-of-use, perceived usefulness, and incentives for ongoing engagement. Additionally, RPM using non-invasive sensors often requires patients to actively obtain and transmit biometric data. These added steps inherently make this strategy more prone to drop off in patient adherence. A strategy to mitigate this added burden on patients is the use of passive approaches to obtain biometric data, including ambient biosensors as described above. Automated data transmission via Bluetooth-enabled devices to a central hub has also become an often-employed strategy across many digital RPM to prevent the need for manual input by patients.

Data transmission, analysis, and presentation

Optimizing clinical alerts

Adoption of RPM for HF management requires clinical integration, into existing workflows and care teams. This often leads to significantly greater volumes of incoming patient data, and can quickly overmatch the capabilities of existing infrastructure and personnel to effectively review.

Optimizing the "signal-to-noise" ratio through the use of clinical alerts, such that clinicians can be directed to review only clinically relevant items, is essential to effective RPM. Systems of alerts have been shown to effectively reduce clinical requirements, however optimizing remains a work in progress. A systematic review examining 9 RPM trials using non-invasive sensing in HF revealed that among studies reporting "patient alerts," patients were contacted only 39% (range: 29–52%) for follow up and management changes.[63] Furthermore, clinical alerts with poor specificity and high false positive rates have demonstrated an increase in unnecessary office visits and hospitalizations.[42] The challenge remains that as RPM continues to expand its footprint, how to further improve the specificity of patient data prioritization so as to avoid clinician "alarm fatigue" while not missing clinically-actionable data.

Ensuring privacy and security

RPM inherently adds additional privacy and security risk, as patient data is being collected and transmitted outside of the traditional healthcare setting. These concerns have been further accentuated amidst the COVID-19 pandemic, with the rapid growth and integration of RPM technologies into healthcare in order to minimize patient exposure.[64] Regulatory bodies and health systems share the responsibility of protecting patient data from use outside its intended purpose and cybersecurity threats. In the US, the Federal Drug Administration (FDA), with support from the Digital Health Center of Excellence, is responsible for pre-market approval of medical devices, which includes ensuring appropriate quality system regulations for cybersecurity are met. However, not all home monitoring technologies, especially certain software and health apps, are considered by definition to be medical devices and thus subject to FDA regulation.[65] Furthermore, federal mandates for patient data privacy through the Health Insurance Portability and Accountability Act (HIPAA) apply to health information if it is generated by a healthcare system, often exempting RPM technology companies.[64] Health systems must therefore appropriately vet RPM technologies prior to partnering to ensure adequate cybersecurity safeguards and protection of patient data.

Care team review and clinical action

Standardized patient management strategies

In addition to PA pressure monitoring, another unique feature of the CHAMPION trial evaluating CardioMEMS was the protocol-defined treatment goal to lower PA pressures when elevated.[25] This, in-turn, led to adjustment of neurohormonal, diuretic, and vasodilator therapies, often in the absence of other clinical decompensation signs. Similarly, the positive TIM-HF2 study employed telemedical analysis software and initial biomarker levels to stratify patients into predefined management strategies.

However, a similar methodology, standardizing the approach to abnormal patient data and alerts, is not present in most major RPM trials employing noninvasive biometric monitoring. In fact, amongst the studies reporting patient alerts, only a minority led to follow up clinical actions.[63] A critical step to promoting effective RPM is ensuring there are corresponding delineated patient management strategies if data abnormalities ("alerts") are present. This will involve a transition from a reactive to proactive management pattern in order to treat patients in the pre-symptomatic phase of clinical decompensation.

Guideline-directed medical therapy titration

Beyond recognition and treatment of clinical decompensation, RPM can also assist with GDMT titration. When delivered at maximally tolerated doses, these medications have demonstrated a mortality benefit in HFrEF patients, and therefore can augment RPM's clinical benefit. In fact, several RPM trials and other remote monitoring interventions have demonstrated a superior ability to increase ACE inhibitor, ARBs, and beta blocker GDMT doses among monitored patients, as compared to conventional management.[12][66] Again, this requires a transition from a reactive to proactive RPM management strategy in order to: 1) recognize patients that would benefit GDMT uptitration (HFrEF patients not on maximally tolerated doses) and 2) integrate medication titration protocols into existing clinical workflows.

Centralized and timely monitoring and management

Amongst RPM studies, a major differentiator was who was conducting patient data review and responsible for associated management changes.

For example, the neutral Tele-HF study took a decentralized approach, monitoring patient data downloaded during working hours by a site coordinator, with abnormal values flagged for individual clinician review.[48] This is as opposed to the positive TIM-HF2 study, which took a centralized approach where all patient data was transferred to telemedical centers with physician-led medical support management with 24/7 coverage.[53] Generally, RPM studies with centralized monitoring and management have demonstrated superior outcomes.[45] This is likely related to more timely response to clinical alerts, and more standardized management strategies.

Promoting clinical adoption/buy-in

Although not easily measured in prior clinical trials, buy-in from the multidisciplinary clinical team is essential for effective RPM adoption and use.

Factors weighing into clinical adoption include perceived clinical utility of the data provided by the RPM platform and integration into existing clinical workflows.[67] Effective approaches to addressing these factors include ensuring RPM interface into the existing EMR, and minimizing RPM-relative duplicative work including documentation. Another strategy

for promoting buy-in is via co-development of the RPM platform by clinical stakeholders. Through iterative rounds of co-design with RPM program developers and clinicians, customized RPM programs can be designed. These RPM strategies are then designed to better meet the needs of the clinical users and associated health system, while providing clinical stakeholders a sense of ownership in the program.

Deriving cost effectiveness

Beyond improving clinical outcomes, successful RPM also depends on its cost effectiveness and incremental value. RPM costs include more than just the purchase of individual devices or technologies, and must also account for ongoing monitoring and medical personnel to review and address RPM-related patient data. These are weighed against the potential cost savings of decreasing preventable HF hospitalizations and associated readmission-related reimbursement penalties, and the potential added revenue with RPM-associated billing.

The cost-effectiveness of CardioMEMS implantation and monitoring versus usual care was evaluated in the CHAMPION trial via a Markov model. Given CardioMEMS monitoring was associated with reduced hospitalizations and increased quality of life assessments, cost-effectiveness for CardioMEMS was averaged to $71,462 per quality-adjusted life-year (QUALY) gained and $48,054 per life-year gained, within conventional willingness-to-pay standards.[68] Additionally, an associated exploratory analysis of CardioMEMS in other HF trial populations with lower hospitalization rates yielded worse comparative cost effectiveness.

Similar cost-effectiveness data have not been recorded among major non-invasive RPM trials. Further study in this study is required in this space, especially to allow for direct comparison between RPM strategies.

However, for now, value assessment for RPM must be derived at the per-patient and the per-RPM strategy level. Patient factors to consider include risk for hospitalization, adherence, and life expectancy. RPM factors to consider include device/technology durability, duration of monitoring, and prior demonstrated effect size of the RPM approach.

CONCLUSION

RPM for HF management has become an increasingly adopted strategy with the goal of improving clinical outcomes. Given the growing HF clinical burden, paired with the economic incentives for employing RPM to optimize HF patients' care, RPM strategies are likely to be further incorporated into HF clinical practice. Further RPM growth is also anticipated given shifting practice patterns following the COVID-19 pandemic.

Current evidence suggests greater efficacy among RPM strategies that use invasive sensors for patient data collection, as compared to those that use non-invasive sensors. Nonetheless, RPM approaches reliant on non-invasive sensors still hold great interest, given their applicability to a larger patient population and lower risks and costs relative to invasive approaches.

Going forward, RPM strategies should focus on selecting patients most likely to benefit from RPM, continuing to identify preclinical indicators of decompensation, and improving patient adherence. Data analysis should be directed at optimizing clinical alerts such that only actionable data is directed for care team review while eliminating false positives that

may result in unnecessary healthcare utilization. Finally, clinical action should emphasize standardized, centralized, and timely patient management. Incorporating emerging biometric data collection tools into RPM strategies has the potential to address these needs. Institution and practice-specific factors must also be considered for effective clinical integration and adoption.

Rigorous study of HF RPM strategies, especially those employing emerging tools, is essential in order to determine their optimal use and benefit. This is especially true given that clinical adoption of many RPM approaches will likely continue to outpace their study. We also await the result of major clinical trials including GUIDE-HF to further inform RPM's impact on clinical outcomes. Health systems, particularly academic medical centers, should strive to continue to bridge the evidence gap, conducting trials to evaluate RPM's clinical efficacy, utility, and value.

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