Remote monitoring in heart failure: current and emerging technologies in the context of the pandemic

Donya Mohebali, Michelle M Kittleson

ABSTRACT
The incidence of heart failure (HF) remains high and patients with HF are at risk for frequent hospitalisations. Remote monitoring technologies may provide early indications of HF decompensation and potentially allow for optimisation of therapy to prevent HF hospitalisations. The need for reliable remote monitoring technology has never been greater as the COVID-19 pandemic has led to the rapid expansion of a new mode of healthcare delivery: the virtual visit. With the convergence of remote monitoring technologies and reliable method of remote healthcare delivery, an understanding of the role of both in the management of patients with HF is critical. In this review, we outline the evidence on current remote monitoring technologies in patients with HF and highlight how these advances may benefit patients in the context of the current pandemic.

INTRODUCTION
Despite advances in the management of heart failure (HF), the incidence of HF hospitalisation remains high, and remote monitoring (RM) technologies may assist in optimisation and implementation of guideline-directed medical therapy to improve the quality of life and outcomes of patients with HF. The principle of RM involves the collection and transmission of clinical data between a patient at a distant location and the clinician through a remote interface so that the clinician may review the data and respond accordingly. RM technologies may involve transmission of patient-obtained weight and vital signs or more advanced physiological markers such as thoracic impedance or intracardiac pressures. Theoretically, these data could provide early indications of decompensation that, if addressed, could prevent HF hospitalisation; such advances have new urgency in the COVID-19 pandemic.

The COVID-19 pandemic has resulted in widespread implementation of stay-at-home orders and physical distancing. While such measures are essential to reduce the spread of COVID-19, they have also hindered the standard approach of HF clinicians, where frequent clinical assessment of evolving symptoms, change in physical examination and titration of guideline-directed medical therapy are essential to mitigate progression and decompensation. But these challenges have also led to opportunities as healthcare systems have rapidly deployed and refined a new model of healthcare: the virtual visit.

This convergence of effective RM techniques with the need for virtual patient care affords the opportunity to better understand the advantages and practical usage of these technologies. In this review, we outline the evidence on current RM technologies in patients with HF and highlight how these advances may benefit patients in the context of the COVID-19 pandemic.

RM TECHNOLOGIES
Remote assessment of vital signs
The cornerstone of HF management is aggressive titration of guideline-directed medical therapy based on symptoms, blood pressure and laboratories to achieve the maximum-tolerated dosages to improve symptoms, reduce hospitalisations and increase survival. Even the most basic RM technology, focusing on patient-acquired vital signs, could theoretically improve HF care.

However, remote assessment of vital signs has not demonstrated uniform evidence of benefit. In SUPPORT-HF2, patients with symptomatic HF, regardless of aetiology, and an HF hospitalisation within the past year or an estimated 1-year mortality >10% were randomised to receive blood pressure monitors and scales with information transmitted to clinicians with alerts to optimise medical therapy. There was no increase in the implementation of guideline-directed medical therapy nor improvement in quality of life. Similarly, in BEAT-HF, patients recently hospitalised for decompensated HF requiring intravenous diuretics were randomised to health coaching telephone calls and transmission of blood pressure, heart rate, symptoms and weight on discharge and there was no reduction in 180-day readmissions.

In the largest trial of telephone-based HF monitoring (Tele-HF), approximately 1600 patients recently hospitalised for HF were randomised to a telephone-based, interactive voice-response system that collected daily symptoms and weight for clinician review. The telemonitoring group was instructed to make daily, toll-free calls; patients used a telephone keypad to respond to questions about general health and HF symptoms. Information was reviewed every weekday, predetermined responses that triggered ‘variances’ to flag clinicians’ attention. However, there was no reduction in readmission or death, perhaps due to poor adherence. If patients did not use the system for two consecutive days, they received a system-generated reminder call and were contacted by site staff to encourage participation, but still 14% of patients in the telemonitoring group never used it, and by the end of 6 months only 55% were still participating.

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In contrast, a beneficial impact of telemonitoring was observed in TIM-HF2. Patients with HF were randomised to usual care or a multicomponent telemonitoring home system with daily wireless transmission of weight, blood pressure, heart rate, heart rhythm, oxygen saturation and self-reported adherence was higher in this study: 97% of patients were compliant with daily data transfer and there was a reduction in unplanned cardiovascular hospitalisations (days lost to hospitalisation 18 days vs 24 days) and all-cause mortality (7.9 per 100 person-years vs 11.3 per 100 person-years).2

In summary, RM of vital signs has shown mixed results, perhaps related to variable participation by both the patients (in adhering to data transmission) and the HF clinicians (in having appropriate algorithms to act on available information).

### Remote assessment of lung congestion

Lung congestion can be assessed by thoracic impedance or tissue dielectric properties. Thoracic impedance relies on the principle that electricity travels better through fluid than through bone, tissue or air, and thus less resistance or ‘impedance’ is measured in patients with lung congestion. Cardiovascular implantable electronic devices, including pacemakers and implantable cardioverter defibrillators, can measure thoracic impedance across the generator on the chest wall to electrical leads in the heart. Remote dielectric sensing (ReDS), on the other hand, measures the dielectric properties of tissues. Low-power electromagnetic signals are emitted across the thorax through the lung and the characteristics of the signals received are determined by the lung’s fluid content. In contrast to assessment of thoracic impedance via implanted devices, ReDS monitoring requires a wearable device.

### Table 1  Anticipated barriers to success of remote monitoring technologies and potential solutions

<table>
<thead>
<tr>
<th>Barriers</th>
<th>Solutions</th>
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<tbody>
<tr>
<td>Low patient adherence for data transmission.</td>
<td>Weekly patient reminders to transmit data.</td>
</tr>
<tr>
<td>Poor accuracy of data collected.</td>
<td>Use repeated measurements to confirm accuracy of collected data.</td>
</tr>
<tr>
<td>Lack of clear action plan to interpret data received and respond to alerts.</td>
<td>Create a standardised strategy on how to respond to alerts using automated systems and prompts to healthcare professionals.</td>
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<tr>
<td>Absence of or ineffective management algorithm for the data received.</td>
<td>Formalise and validate algorithms for management strategies using data interpretation.</td>
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</tbody>
</table>

### Table 2  Summary of clinical trials of remote monitoring technologies

<table>
<thead>
<tr>
<th>Type of monitoring</th>
<th>Study</th>
<th>Device/monitoring variables</th>
<th>Hospitalisations</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mortality</td>
</tr>
<tr>
<td>Weight/home measurements</td>
<td>Chaudhry et al (Tele-HF)</td>
<td>Symptoms and weights.</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>Kohler et al (TIM-HF)</td>
<td>EKG, BP and weight.</td>
<td>↓</td>
</tr>
<tr>
<td></td>
<td>Org et al (BEAT-HF)</td>
<td>Symptoms, HR, BP and weight.</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>Böhm et al (Opti-Link HF)</td>
<td>ICD-based thoracic impedance monitoring.</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>Domenichini et al (UMIT-CHEF)</td>
<td>ICD-based or CRT-based thoracic impedance monitoring.</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>von Velthuijsen et al (DOT-HF)</td>
<td>ICD-based thoracic impedance monitoring.</td>
<td>x</td>
</tr>
<tr>
<td>Haemodynamics</td>
<td>Abraham et al (CHAMPION)</td>
<td>Pulmonary artery pressure monitoring.</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>Abraham et al (LAPTOP-HF)</td>
<td>Left atrial pressure monitoring.</td>
<td>↓</td>
</tr>
<tr>
<td></td>
<td>Adamson et al</td>
<td>Pulmonary artery pressure monitoring.</td>
<td>↓</td>
</tr>
<tr>
<td></td>
<td>Givertz et al (MUSE)</td>
<td>Pulmonary artery pressure monitoring + GDMT.</td>
<td>↓</td>
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<tr>
<td></td>
<td>Desai et al</td>
<td>Pulmonary artery pressure monitoring.</td>
<td>↓</td>
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<tr>
<td></td>
<td>Shavelle et al</td>
<td>Pulmonary artery pressure monitoring.</td>
<td>↓</td>
</tr>
<tr>
<td></td>
<td>Lindenfeld et al (GUIDE-HF)</td>
<td>Pulmonary artery pressure monitoring.</td>
<td>x</td>
</tr>
<tr>
<td>Multiple parameters</td>
<td>Anand et al (MUSIC)</td>
<td>Non-invasive monitoring of HR, RR, thoracic impedance and activity.</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>Borhani et al (MORE-CARE)</td>
<td>CRT-based monitoring of thoracic impedance and atrial tachyarrhythmias.</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>Bozhmer et al (MultISENSE)</td>
<td>CRT-based monitoring of HR, heart sounds, RR, activity and thoracic impedance.</td>
<td>↓</td>
</tr>
<tr>
<td></td>
<td>Morgan et al (REM-HF)</td>
<td>CRT-based monitoring of thoracic impedance, arrhythmia, pacing and HR variability monitoring.</td>
<td>x</td>
</tr>
</tbody>
</table>

Summary of clinical trials and outcomes of remote monitoring technologies of various categories, including weights and home monitoring, thoracic impedance, haemodynamics and multiple combined parameters.

x denotes an outcome that was studied with a neutral outcome.

↓ indicates a reduction in the outcome with the intervention versus standard of care, the comparator arm.

BP, blood pressure; CRT-D, cardiac resynchronisation therapy; EKG, electrocardiogram; GDMT, guideline-directed medical therapy; HR, heart rate; ICD, internal cardiac defibrillator; RR, respiratory rate.
Figure 1  Summary of remote monitoring technologies and devices. PA, pulmonary artery.

Figure 2  Examples of the information provided to clinicians of two remote monitoring devices. (A) Non-invasive pulmonary artery pressure monitoring can be performed with the CardioMEMS system, which provides a centralised database accessible to the clinician with the trend of pulmonary artery pressures. (B) Thoracic impedance can be assessed with cardiac implanted electrical devices such as pacemakers and implantable defibrillators. In this example, the reduction in thoracic impedance (arrow) suggests increased pulmonary congestion. PA, pulmonary artery.
Thoracic impedance has not emerged as an important RM tool. One potential explanation for the lack of benefit of thoracic impedance assessment may be the low sensitivity, measured at approximately 30% for clinically adjudicated pulmonary congestion in one study and 20% for HF hospitalisations in another.\(^1\)

Automated fluid status alert notifications to treating clinicians based on changes in thoracic impedance do not result in a reduction in death or HF hospitalisations,\(^1\) even when these alerts trigger an automatic 50% increase in diuretic dosage after alert notification.\(^1\) These negative findings of the impact of RM of thoracic impedance were confirmed in a meta-analysis of 4 randomised trials and 1290 patients.\(^1\)

In addition to lack of benefit, one study demonstrated potential harm: when patients and physicians had access to audible alerts indicating reduced thoracic impedance, there was an increase in outpatient visits and HF hospitalisations, although there was no difference in symptoms and signs of HF, suggesting that a large portion of the extra medical visits were triggered by alerts instead of decompensated HF.\(^1\)

More encouraging results of ReDS technology were observed in a randomised trial of 268 recently hospitalised patients with HF. Those discharged home with the ReDS fluid monitor system instead of decompensated HF.\(^1\) Remote daily telemonitoring and remote follow-up audio/video conference.\(^1\) Heart Failure Study to Evaluate Vital Signs and Overcome Low Use of Guideline-Directed Therapy by Remote Monitoring (HF-eVOLUTION)\(^2\) Biobeat wrist watch for continuous measurement and reporting of blood pressure data and with a smartphone to report weight.\(^1\) Efficacy, Safety and Cost of Remote Monitoring of Patients with Cardiac Resynchronization Therapy (ECOST-CRT)\(^3\) Remote notification of HF parameters, atrial arrhythmias and patient’s symptoms and signs.\(^1\) Daily Ambulatory Remote Monitoring System For Post-Discharge Management Of AHF/DHF (DAVID-HF)\(^4\) Remotely collected physiological data obtained from home-based wearable devices.\(^1\) Effects of Remote Monitoring of Patients With Heart Failure Based on Smartphone Application (ERICA-HF)\(^5\) Remote monitoring with a mobile application which will assess dyspnoea, position in bed, oedema, weight change, blood pressure and heart rate.\(^1\) Patient Self-Monitoring With Hemodynamic Monitoring Virtual Heart Failure Clinic and Outcomes (SELFie-HF)\(^6\) CardioMEMS HF sensor to monitor pulmonary artery pressures.\(^1\) Remote monitoring Analytics in HF (LINK-HF2)\(^7\) Clinical parameters from a small wearable sensor.\(^1\) Multiple Cardiac Sensors for the Management of Heart Failure (MANAGE-HF)\(^8\) Remote monitoring of S1 and S3 heart sounds, night-time heart rate, thoracic impedance and respiration from the Heartlogic feature of implanted CRT-D or ICD devices.

Remote assessment of haemodynamics

More sophisticated RM technologies rely on implantable intra-cardiac devices to directly measure cardiac pressures. The two most widely studied are (1) pulmonary artery (PA) pressure monitor (CardioMEMS), which comprised a lead-less, battery-less pressure sensor percutaneously implanted in the PA; and (2) left atrial pressure transducer (HeartPod) placed percutaneously via trans-septal puncture within the interatrial septum with a communications module placed in a subcutaneous pocket.

Unlike PA pressure monitors, left atrial pressure transducers have not demonstrated benefit. In LAPTOP-HF, patients transmitted left atrial pressure measurements and adjusted diuretic and vasodilator therapy based on a standard algorithm. While there was a reduction in HF hospitalisations in the intervention group, the study was terminated early by the data safety monitoring board due to a number of implant-related trans-septal complications, including cardiac perforations that required pericardiocentesis or surgical repair.\(^1\)

On the other hand, in the CHAMPION-HF trial, patients with symptomatic HF regardless of ejection fraction randomised to PA pressure monitoring versus usual care had a 37% reduction in HF hospitalisations over 15 months.\(^1\) This benefit was noted in post-hoc analyses of patients with HF with both preserved and reduced ejection fraction.\(^1\) PA-pressure monitoring also reduces HF hospitalisations in routine clinical practice.\(^1\) In one study, the mean rate of daily pressure transmission was 76%, suggesting that patient adherence to monitoring may be one component of its success.\(^1\)
Another component of CardioMEMS’ success may be the appropriate adjustment of medical therapy. In CHAMPION-HF, the active monitoring group had greater targeted intensification of diuretics and vasodilators and preservation of renal function despite diuretic intensification. The real-time frequent assessment of PA pressures may provide an antidote against therapeutic inertia; this targeted approach proved more effective in reducing HF hospitalisations than management of clinical signs or symptoms.

The CardioMEMS device is approved by the US Food and Drug Administration to wirelessly monitor PA pressure and heart rate in New York Heart Association class III patients who have been hospitalised for HF in the previous year. The GUIDE-HF (Guided Management of Heart Failure) trial is a prospective trial which will determine if the benefit of treating PA pressures may provide an antidote against therapeutic inertia; this targeted approach proved more effective in reducing HF hospitalisations than management of clinical signs or symptoms.

Factors leading to virtual visit accessibility and availability including policy changes, clinician acceptance and patient acceptance. EMR, electronic medical record.

Multiple parameters platforms
Conceptually, combining measurements that individually can detect worsening HF into a multiparameter platform should improve the ability to identify and prevent HF decompensations, although this has not yet been borne out in randomised trials.

Monitoring thoracic impedance, heart rate variability and activity had no impact on cardiovascular hospitalisations or death in one study, but this may have been because the algorithm for managing the information collected was unclear. Monitoring thoracic impedance and atrial arrhythmias with an algorithm for managing alerts also did not impact HF hospitalisations or deaths, although there was a decrease in emergency department and office visits after 2 years. This study was prematurely terminated due to slow enrolment and with approximately one-third of patients having incomplete follow-up. Thus, one barrier to success may be patient adherence. Another may be that the predictive accuracy of the specific combinations of parameters has not been established.

Nonetheless, the predictive accuracy of some multiparameter platforms has been investigated. An algorithm based on heart rate, respiratory rate, activity and impedance from an external adherent system was able to predict HF events with a sensitivity of 63% and specificity of 92%. Although this device has yet to be tested in a randomised controlled trial with a specific intervention or clinical outcome measure. A machine learning algorithm using continuously streaming data on heart rate, heart rate variability, arrhythmia burden, respiratory rate, gross activity, walking, sleep, body tilt and body posture from a wearable sensor (VitalConnect) was able to detect precursors of HF hospitalisations with 76%–88% sensitivity and 85% specificity; the median time between initial alert and readmission was 6.5 days.

Sensors from cardiac resynchronisation therapy defibrillator (CRT-D) devices (the HeartLogic diagnostic feature) to monitor heart sounds, respiratory rate and relative tidal volume were used to develop an algorithm which predicted the risk of HF with 70% sensitivity and 86% specificity. Furthermore, in patients whose parameters exceeded the alert threshold, there was a 10-fold increased risk of a subsequent HF event.

Whether this benefit withstands the test of a randomised trial will be assessed in the MANAGE-HF (Multiple Cardiac Sensors for the Management of Heart Failure) study, a multiphase study designed to evaluate the clinical integration and utilisation of the HeartLogic diagnostic feature and its impact on HF hospitalisation and inpatient mortality in patients implanted with CRT-D or internal cardiac defibrillator devices.

The success of multiparameter technology will depend on patient adherence and the predictive accuracy of management algorithms. Randomised assessment of their impact on cardiovascular hospitalisations and death will be essential before they enter clinical practice. A summary can be found in table 2 and figures 1 and 2. An overview of ongoing trials is summarised in table 3.

COVID-19 AND RM TECHNOLOGY
The impact of COVID-19 on patients with HF
With widely mandated stay-at-home orders and fear of contamination, the COVID-19 pandemic has created barriers to healthy
lifestyle practices and routine medical care to which patients with HF are particularly vulnerable. In a telephone survey of 124 patients with HF from the Dijon University Hospital Heart Failure Clinic during the sixth and seventh weeks of the lockdown in France, 18.5% reported greater psychological distress, 41.9% had decreased physical activity, 14.5% reduced their energy expenditure, 30 an Italian study suggests that it is because to less dietary indiscretion, better medication adherence or less mobility or transportation may still receive medical attention; and (3) technology was implemented to integrate these visits into many electronic medical records systems (figure 4).

The key to successful virtual visits is to use the same systematic evaluation that one would perform during an inperson visit. Table 4 outlines a useful checklist of high-yield assessments for history and physical examination and other key components of the virtual visit. Of note, evaluation of neck veins over a virtual platform is possible and accurate; in one analysis, there was 90% agreement with Jugular venous pulse estimation at the bedside or remotely when the right atrial pressure was over 10 mm Hg. The advantages of virtual visits are clear: patients with limited mobility or transportation may still receive medical attention; care by pharmacists, social workers and nutritionists can be more easily coordinated; and caregivers may be present and educated regarding the treatment plan. However, it is essential to determine which patients will not fare well with virtual visits.

Vulnerable patient populations, including those with limited access to the internet or devices that are used for virtual visits, in addition to older adults with visual, auditory and cognitive impairments, may not be able to communicate adequately via a virtual platform. Most importantly, patients who are at high risk for decompensation may require inperson assessments instead of virtual visits.

The role of RM in the pandemic
To date, there is little published experience on the use of RM technologies in the pandemic as an adjunct to virtual visits. In a study of 21 patients in Massachusetts with HF and implantable PA pressure monitors (CardioMEMS), there were more PA pressure deviations from the preset threshold during the COVID-19 pandemic, accompanied by doubling in the number of clinician–patient encounters yet fewer HF admissions. These observations suggest that the lower rates of HF hospitalisations were not entirely related to patients’ hesitance to seek medical care but were at least partially due to effective remote management. 33 In another study of 40 patients in New York, there were more transmissions by patients and interventions by clinicians, no difference in mean PA diastolic pressures, and fewer HF hospitalisations during versus prior to COVID-19. 34 These small studies provide a model for use of PA pressure assessment in conjunction with virtual visits to guide HF management.

The rise of virtual visits
One silver lining of the pandemic may be the rapid deployment of virtual visit technology, where necessity resulted in several simultaneous advances, transforming this heretofore untenable method of healthcare delivery rapidly into a reality: (1) clinicians and patients accepted the utility of this approach; (2) federal governing bodies, including the US Department of Health and Human Services and the Centers for Medicare & Medicaid Services, relaxed previous requirements and allowed reimbursement; and (3) technology was implemented to integrate these visits into many electronic medical records systems (figure 4).
CONCLUSION AND FUTURE DIRECTIONS

Despite the disruptions that COVID-19 had caused to our healthcare systems, there is cause for optimism. The combination of RM, particularly with PA pressure sensors, and the rise of virtual visits will allow the physician–patient connection to be maintained and strengthened. For now, these two areas of advancement have progressed in parallel with only anecdotal insight into potential benefit.

Future research should focus on the impact of RM combined with virtual visits on HF outcomes, the validation and incorporation of information gleaned from RM into algorithms used as part of virtual visits, and the barriers to successful implementation of these strategies, especially in the context of healthcare disparities.

We should strive for a post-COVID-19 world that maintains the infrastructure of virtual visits with a seamless component of RM technologies as the novel use of both resources will benefit both the healthcare professionals and their patients long after this pandemic has ended.

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