Data driven monitoring in patients on left ventricular assist device support

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Key words: Left ventricular assist device, LVAD, Remote monitoring, Algorithms, Prediction, Circadian rhythm

Abstract

Introduction: Despite an increasing population of patients supported with a left ventricular assist device (LVAD), it remains a complex therapy, and patients are frequently admitted. Therefore, a strict follow-up including frequent hospital visits, patient self-management and telemonitoring is needed.

Areas covered: The current review describes the principles of LVADs, the possibilities of (tele)monitoring using non-invasive and invasive devices. Furthermore, possibilities, challenges and future perspectives in this emerging field are discussed.

Expert Opinion: Several studies described initial experiences on telemonitoring in LVAD patients, using mobile phone applications to collect clinical data and pump data. This may replace frequent hospital visits in near future. In addition, algorithms were developed aiming to early detect pump thrombosis or driveline infections. Since not all complications are reflected by pump parameters, data from different sources should be combined to detect a broader spectrum of complications in an early stage. We need to focus on the development of sophisticated but understandable algorithms and infrastructure combining different data sources, while addressing essential aspects such as data safety, privacy and cost-effectiveness.

Article Highlights

- Telemonitoring in patients after LVAD support is broadly recognized as a valuable tool to further improve outcome, but not yet implemented on a large scale.
- Currently most implanted LVADs are limited in data storage and transmission, which hampers the development of AI-based prediction algorithms
- Data from different sources should be combined to further improve the prediction performance of algorithms that can be used to remotely monitor LVAD patients
- The main barrier of large-scale implementation of telemonitoring is to set-up a new infrastructure and integration in standard clinical care pathways, for a relatively small patient group.

Key words: Left ventricular assist device, LVAD, Telemonitoring, Algorithms, Prediction, Circadian rhythm

1. Introduction

The number of patients receiving a left ventricular assist device (LVAD) continuously increases due to the limited number of donor hearts and the increasing population of patients with end-stage heart failure.[1][2] LVADs were initially implanted as a bridge to transplantation, but were also established as destination therapy driven by technical enhancements and tremendous improvement in patient survival.[3] Nevertheless, LVAD patient care remains very complex, and patients are frequently admitted for serious complications.[4] A strict follow-up including frequent outpatient clinic visits and patient self-management is therefore required. A multidisciplinary team with cardiologists, cardiothoracic surgeons, physician assistants, nurse practitioners, VAD coordinators, and social workers collaborate to provide complex LVAD patient care.[5] Nevertheless, up to 80% of the patients are readmitted within the first year after implantation.[6] Therefore, telemonitoring may further improve clinical outcome in LVAD patients by early detection of deterioration. In addition it could also reduce the number of unnecessary hospital visits. This is especially beneficial for patients who have a long travel distance to an LVAD center. Telemonitoring may improve the quality of life of patients on LVAD support, while being a cost-effective method. LVAD patients can be monitored on different aspects, such as LVAD controller parameters, blood pressure, pacemaker, implantable cardioverter defibrillator (ICD) or cardiac resynchronization therapy (CRT), coagulation values and medication and further parameters and findings that can be transmitted by a smartphone such as driveline photo's or activity.[7] The aim of the current review is to discuss the possibilities of such methods and initial experiences of telemonitoring in LVAD patients. At first, a short introduction on LVADs is provided and lastly, possibilities, challenges and future perspectives in this emerging field are discussed.

2. Left ventricular assist device

Figure 1 depicts all components of an LVAD. The implanted components are the inflow cannula, which is implanted into the apex of the left ventricle (LV) and an impeller that circulates blood towards the outflow graft connecting to the aorta. The pump is connected via a driveline to an external controller with two batteries. The controller can be attached to a monitor, which allows for data retrieval. The speed of the pump is set by clinicians and optimized using echocardiography. Currently, most patients have a HeartMate 3 (HM3, Abbott, Chicago, IL, USA) or HeartWare (HVAD, Medtronic, Minneapolis, MN, USA), which was recently withdrawn from the global market.[8] Those commonly used LVADs store the speed of the rotor, the power, the calculated flow, the pulse index (PI) or pulsatility, alarms and events. HM3 has an intrinsic pulse mode aiming to reduce blood stasis in the pump and minimizing thrombus formation.[9] Both HM3 and HVAD alarm if the flow drops below the pre-set threshold mostly at 2.5 L/min, and HVAD alarms if the power is > 2 Watts above the average power.

3. Monitoring of LVAD pump parameters

LVAD pump parameters are currently mostly monitored in hospital at the outpatient clinic. Those are crucial for clinical assessment, as they are often affected in case of abnormalities. LVAD pump parameters are stored and can be retrieved by connecting the controller to a monitor. Currently it is impossible to retrieve data remotely due to the requirement of the physical attachment to the monitor located in-hospital. Data storage is rather limited, i.e. one sample every 15 minutes for HVAD or maximal 256 samples for HM3. In contrast, both the HeartAssist 5 (HA5, MicroMed Cardiovascular, Inc., Houston, TX, USA) and aVAD (ReliantHeart Inc., Houston, TX, USA) allow for telemonitoring. Both axial flow devices contain an ultrasonic flow probe on the outflow graft. Patients connect to a portable console to transmit the data to a secured central server using standard cellular network. Caregivers can assess the data on a website. A ten-second high resolution and real-time waveform can be requested.[10][11] Even though those devices are not implanted on a large scale, since axial flow devices have been proven to be

inferior to centrifugal pumps, their possibility to remotely assess pump parameters should be recognized in future LVAD designs.[12] Although the diagnosis of complications in LVAD patients is never solely based on pump parameters, it is a valuable tool in the clinical assessment (table 1). Notably, not all complications are reflected by the pump parameters.

Despite the low occurrence, a much feared complication in patients on LVAD support is pump thrombosis (PT). The risk for thrombosis after LVAD implantation increases due to the exposure to foreign surfaces and regions of blood stasis. Cessation reduction of anti-platelet therapy to treat major bleeding may increase the risk of a thromboembolic event.[13] In addition, poorly controlled hypertension results in a decreased LVAD flow, which can also contribute to thrombus formation, that may result in PT or an ischemic stroke.[14] Several studies focused on the development and evaluation of algorithms, aiming for detection of pump thrombosis at an early stage.[15]–[19] The prevailing variable that was monitored in those algorithms is the pump power. During the development of pump thrombosis, the formation of a blood clot results in a surge in power consumption since it tries to maintain the set speed, and will also cause a falsely elevated pump flow estimation.[18], [19] Although for example HVAD has a standard-of-care threshold to detect “High Watt” alarms, more sensitive settings for pump power may enable earlier detection. Slaughter et al. developed an algorithm based on four detectors, including short and longer trends, comparing power to population norms, and a detector for the initial phase where no patient-specific estimates were present. Testing the algorithm retrospectively, they identified pump thrombosis on average four days before clinical presentation, with a sensitivity of 85%.[15] In addition to trends in pump power, the circadian rhythm of pump parameters may add valuable information. Consolo et al. showed that patients gain physiological circadian (24-hour) rhythmicity in their pump parameters during the initial post-operative period, which remains stable in the long term. The circadian rhythm is diminished during the early stages of pump thrombosis, providing the opportunity to detect pump thrombosis at an early stage. After the resolution of the thrombus, a stable circadian rhythm reemerges.[16] However, enabling the incorporation of the circadian rhythm into an algorithm requires high resolution datasets. A thrombus may also arise in the outflow graft, resulting in an outflow graft obstruction. In addition, the outflow graft can be obstructed by kinking of the graft or external compression of the graft. Commonly it results in a decrease in flow over several weeks, but may also abruptly cause a decreased flow.[20]

On the other side of the spectrum there is an increased bleeding risk, which instead may lead to a decreased power, flow and increased PI (table 1). Also, the circadian rhythm of power and flow may diminish.[21] It can have several causes, such as intrinsic coagulopathies or over-anticoagulation for example due to liver congestion. Moreover, there is an increased risk for a bleeding event following treatment of a thrombotic event due to cessation of anticoagulation therapy.[22] However, bleeding complications such as a hemorrhagic stroke are not caused by anticoagulation therapy alone, as a supra therapeutic INR is neither necessary nor sufficient to cause a hemorrhagic stroke.[23] In addition, patients on LVAD support often suffer from acquired von Willebrand syndrome, where the Von Willebrand Factors (VWF) are structurally misshaped due to increased shear stress, leading to an increased bleeding risk. Bleeding in the gastro-intestinal tract (GI) often occurs at the location of an arteriovenous malformation (AVM) that arise as a consequence of diminished pulsatility.[24] No studies specifically focused on detecting such patterns in pump power, but algorithms developed for pump thrombosis may be applicable as well.

In addition to bleeding and thrombosis risks, patients are at risk of right ventricular (RV) failure, which may occur early after implantation or in the long term.[25] The right ventricle output needs to match the increased flow generated by the device. The optimal pump speed is determined using echocardiography to ensure that the septum is in the midline. With a septal shift towards the left side, the efficiency of the RV

contraction is negatively affected, since the contribution of the septum to RV contraction is diminished, which needs to be compensated by the RV free wall, leading to failure.[26][27] If RV failure leads to a significant reduction in preload for the left ventricle, it is accompanied by a reduced LVAD pump power and flow. However, diagnosis is mostly done using echocardiography.

Other important complications that may be reflected by pump parameters and occur as a consequence or aggravate after LVAD implantation are ventricular arrhythmias (VAs) and atrial arrhythmias (AA). VA occurs in 20-60% of the patients and is more frequently diagnosed in the initial postoperative period with a U-shaped incidence over time.[28] Fibrosis, ischemia, inotropic and vasopressor medication, or suction events may cause VAs. Suction is the occurrence where the septum occludes the inflow cannula, caused by a mismatch in preload and pump speed, resulting in a sudden drop in pump flow. When de instantaneous and 15-second average PI differ by more than 45%, a so called "PI-event" is stored and the speed drops to its pre-set low speed, and increases gradually to the normal speed. Gross et al. revealed high suction rates in clinically stable outpatients which reveals the importance of the development of early detection algorithms, since suction may lead to irritation of cardiac tissue and arrhythmias.[29] Moreover, an algorithm was built to early detect suction, which can be used as a diagnostic tool or as an automatic physiological controller.[30] Both suction and arrhythmias result in a decreased power and flow, and may cause either increased or decreased PI.

4. Monitoring medication adherence

Patients on LVAD support require anticoagulation medication. The current guidelines recommend a vitamin K-antagonist (e.g. warfarin) and aspirin with an international normalized ratio (INR) target range of 2.0-3.0.[31] Optimizing anticoagulation is challenging, since there is a small therapeutic range between bleeding and thrombotic risks in LVAD patients.[32] INR is measured several times per week to monitor anticoagulation status. The workflow of INR measurement differs per center and country and may even differ within centers. It may comprise self-monitoring (self-testing), self-management (self-testing and self-dosage), or it is managed by an anticoagulation management clinic or service.[33] Self-management of INR after intensive training by experienced staff is superior regarding the time in the therapeutic range when compared to telemedical-based INR management.[34] Self-management of INR is not standard care yet and may not be suitable to all patients. Some centers have experience in structured phone consultation or using mobile apps where INR measurements are transmitted. In addition to INR as a tool to monitor the effect of anticoagulation, the mean arterial pressure (MAP) is important to follow-up, since a higher MAP is associated with an increased risk of stroke during LVAD support.[35][36][37] Therefore, blood pressure management is very important, and experts recommend to maintain the MAP below 85 mmHg.[38] Therefore, many patients receive Angiotensin-converting enzyme (ACE) inhibitors and angiotensin II receptor blockers. To check whether the blood pressure lowering medication is sufficient, the MAP is measured. Blood pressure measurement is challenging in patients on continuous flow LVAD, due to a diminished pulsatility. Therefore, the MAP is preferably measured using a Doppler or a slow cuff device.[39] Slow cuff devices were reported to perform most optimally.[40] The majority of patients do not have such device at home and therefore MAP is often only measured at the outpatient clinic or transmitted via a mobile phone application.

5 Monitoring using non-invasive devices

Even though telemonitoring has been recognized as a relevant topic, telemonitoring programs for LVAD patients have not been implemented on a large scale yet.[7] A few studies evaluated the feasibility of telemonitoring using mobile phone applications or structured phone consultations and their effect on patient outcomes in patients on LVAD support.[41]–[44]

Casida et al. developed an application for LVAD patients to improve self-management and allow caregivers to monitor their patients remotely.[41] The application's content included questions on the functionality of the LVAD system and its components, evaluation of LVAD parameters, symptoms, body weight, lab tests, driveline, the color of urine and stool, diet, and fluid intake allowance. They demonstrated that it was feasible for both patients and caregivers to use an app as a telemonitoring tool. Patients and caregivers reported high acceptability and usability scores. In addition, Patel et al. evaluated a virtual care platform for telemonitoring of LVAD patients.[44] Their platform included monitoring of LVAD parameters and medication adherence, a two-way messaging function and educational videos (i.e., on troubleshooting). Patients who used the platform (n=25) had significantly less outpatient visits when compared to the control group (n=77), but no difference was found in 30-day readmission rates. Although 3 out of 25 patients showed engagement rates below 10%, the median overall engagement rate was 73%. No false alarm rate or burden was reported, and workload for healthcare professionals was not discussed. Although feasibility is demonstrated in small studies, additional research needs to expel long-term acceptance, usability, adherence and cost-effectiveness. Furthermore, Schmidt et al. developed a smartphone application where different relevant parameters can be sent daily to the LVAD center. Using the application, weight, INR, medication, symptoms and LVAD parameters and driveline photos can be evaluated at the hospital. They studied usability, acceptable and functionality of the application in 13 patients for four weeks. Usability was scored 4.8 out of 5 by patients and the software was stable. Most alarms were caused by deviations in INR. They acknowledge that larger and long term studies are required to prove its added value, also to test the impact on the psychological aspect of patients.[45]

Comparable to mobile phone applications, telephone-based monitoring strategies have been reported.[42], [43] Although in literature structured telephone consultation solely is not considered as telemonitoring, it is considered valuable in order to (further) develop telemonitoring strategies. For example, the algorithm developed by Schlöglhofer et al. that determines the level of patient severity[42], can directly be transferred to application based telemonitoring and are considered a valuable step towards more automated assessment of relevant LVAD-related data. They developed a standardized telephone intervention algorithm, where patients were called every two weeks. Nurses used a flowchart with questions on pump parameters and general well-being, INR, weight MAP, temperature, dyspnea, peripheral edema, and the driveline.[42] Patients were randomized into either the intervention arm or the control arm. A high patient acceptance was reported in the intervention arm. In 42.5% of the calls a problem was identified, regarding elevated blood pressure, edema, INR outside the therapeutic range or exit-site problems. The additional workload for nurses was not discussed. Despite the small size of their study, with only 25 patients in the intervention group, the study touched upon the possibilities of additional monitoring of LVAD patients, with a significantly better survival in the intervention arm. Cost-effectiveness was not assessed in their study and remained to be investigated. In addition, Mariani et al. developed a phone-based monitoring strategy during the initial coronavirus disease 2019 (COVID-19) outbreak.[43] Patients were allowed to enter the monitoring program after extensive training. During a weekly phone call, questions were asked following a developed questionnaire including COVID-related questions in addition to LVAD-specific questions on flow, speed, power, INR, weight, and driveline status. If necessary, the patient sent a photo of the driveline exit site via email or by phone. The pandemic may have accelerated the development of such programs. To improve the workflow of sending driveline photo’s, an application was developed by Lüneburg et al., who used a machine learning algorithm to classify photos of driveline exit sites in either no infection, mild infection, or severe infection. Driveline infections are associated with an increased risk of sepsis, ischemic stroke and mortality.[46][47][48][49] The algorithm that was built by Lüneburg et al. included assessing out-of-focus images, segmentation of the driveline, prediction of the region of interest, and infection classification. Their infection classification algorithm had an accuracy of 67%. Although in typical machine learning applications, 90% or higher

accuracy is expected and desired, their algorithm performed better than pure visual recognition by nurses.[50] Its performance is expected to increase with larger datasets. Such tools may be used to pre-select cases that certainly need priority. Future prospective studies are warranted to prove the effectiveness of such algorithms.

In addition to mobile phone strategies, other non-invasive devices may be used to early detect adverse events. Kaufmann et al. studied the possibilities of acoustic measurements in LVAD patients and demonstrated that a sound peak in a specific frequency band correlates with the presence of thrombi inside the pump. In addition, an increase of 75% in the sound amplitude of the rotary frequency indicates pump thrombosis. They concluded that analysis of the acoustic spectrum of an LVAD using a microphone is a reliable method to detect pump thrombosis.[51] In addition, Boilson et al. showed alterations in the amplitude of higher-order harmonics in patients on HMII support diagnosed with pump thrombosis.[52] Those acoustic measurements were performed in-hospital. In contrast, Mainsah et al. analyzed acoustic measurements at home, where patients were instructed to perform 1-minute recordings weekly.[53] It remains to be investigated whether such acoustic methods contribute to the current practice. Detection of gradual increase in pump power or spikes in pump power may also identify pump thrombosis at an early stage without the need of an additional device. These methods should be compared in future studies. Another aspect that can be monitored non-invasively is activity. Although not studied extensively, two case examples were shown where the activity level of LVAD patients dropped several weeks before readmission.[21] However, these were only case reports and larger-scale studies are required to prove their feasibility and additional value.

6. Monitoring using implantable devices

In addition to non-invasive tools, invasive or implantable devices may be used to remotely monitor LVAD patients. Although not frequently used in combination with LVADs, the safety and feasibility of the CardioMEMS (Abbott Inc, Atlanta, GA, USA) in LVAD patients have been demonstrated.[54] The CardioMEMS, which measures pulmonary artery pressure, provides daily insight into a patient's fluid status, enabling optimization of patients prior to LVAD implantation. In addition, pulmonary artery pressure lowering medication can be monitored. Several complications such as tamponade, aortic valve regurgitation, pump thrombosis, right heart failure or significant hemodynamic arrhythmias will lead to either congestion or reduced pulmonary artery pressure, which may be detected using the CardioMEMS sensor.[55] Likewise, it allows for telemonitoring after LVAD implantation. Zhou et al. incorporated a pressure sensor into the LVAD inlet in an experimental set-up. This enables a direct measure of the left ventricle function during LVAD support.[56] They stated that this is the start of a closed loop speed control based on left ventricular pressure. Although pressure sensors or flow probes may provide valuable information, durability and reliability should be tested extensively in-vivo. The more components a device includes, the more prone it is to malfunctioning and failure. Future studies are warranted to prove its added value. Noteworthy, cost-effectiveness is not touched upon yet, and we may need to focus on more accessible and noninvasive telemonitoring tools first.

Almost 80% of the patients on LVAD support have also an ICD implanted, either with or without CRT.[57] In addition to heart rhythm, heart rate variability and thoracic impedance are measured. This provides an additional source of data to integrate with pump parameters to develop a prediction model for adverse events. Bartoli et al. described a case where intrathoracic impedance measured by a pacemaker increased preceding suction events, low flow alarms, and worsening of heart failure symptoms.[58] HeartLogic (Boston Scientific, Massachusetts, USA) developed an algorithm to early detect deterioration in heart failure patients and is available in both ICDs and CRTs.[59] The algorithm uses the first and third heart sounds, thoracic impedance, respiration rate, tidal volume, heart rate, and activity. Feasibility was shown

in two patients on LVAD support.[60] Further research is needed to study the added value of monitoring LVAD patients using systems like HeartLogic. Combining an algorithm such as HeartLogic and pump parameters could further improve the prediction of adverse events, although limitations exist due to different vendor systems to integrate data flows into a real-time predictive model.

7. Conclusion

The interest in telemonitoring as addition to the current clinical follow-up for LVAD patients has increased over the last decade. Despite broad recognition of its importance, telemonitoring in LVAD patients has not yet been fully explored nor integrated into standard care. We provided an overview of different strategies aiming to early detect adverse events. In addition to standard clinical care, mobile phone applications or phone-based strategies, other implanted or non-invasive devices, and sophisticated algorithms may further improve both quality of life and survival in patients on LVAD support. A future challenge is to develop the infrastructure that enables to integrate data from different sources and vendors. Sophisticated, modular and patient-specific algorithms are desired to further optimize LVAD patient care. Large scale implementation studies are needed across different healthcare systems to optimize LVAD care pathways. Finally, additional studies are warranted to address the cost-effectiveness of such telemonitoring strategies.

8. Expert opinion: Challenges and future perspectives

In the current review we described the necessity of (tele)monitoring for LVAD patients, its current forms and initial experiences. Figure 2 summarizes aspects that can be monitored in LVAD patients. Several studies were discussed showing initial experience with additional forms of monitoring patients outside hospital, utilizing phone based applications, structured telephone intervention or invasive devices. In addition to its potential to improve survival and quality of life of LVAD patients, telemonitoring could also reduce healthcare costs by diminishing the number of unplanned readmissions by early detection and intervention. In future, this may reduce the number of hospital visits. However, at the moment, experts suggest to use telemonitoring as a substitute to rather than replacing routine clinical visits.[45][38][61] Moreover, completely replacing personal contact with medical staff was not considered as a good development.[45] Although telemonitoring for LVAD patients seems feasible, we need to overcome several barriers.

One of the main barriers is the development of the data infrastructure. This requires a major investment both in resources and time, while cost-effectiveness remains to be proven. Advancements in the development and implementation of telemonitoring for LVAD are lagging behind compared to the general heart failure population, since patient groups are relatively small. Therefore, it receives less attention, while LVAD patients who may especially benefit from telemonitoring due to the complexity and risk of LVAD therapy. In addition because LVAD patients already have several sensors as of their implanted devices that result in parameters that can be monitored.[61] Experience in telemonitoring programs used in other patient groups may benefit the realization of such methods specifically for LVAD patients. Researchers should collaborate with different LVAD-centers, but also with industry. This is expected to accelerate development and implementation of telemonitoring techniques. Due to the limited patient numbers per center, we should set-up multi-center studies to collect larger data-sets that can be used to further improve algorithms that can be used in telemonitoring methods. Application-based telemonitoring methods offer other advantages beyond telemonitoring of patients, such as centralized communication between nurses and patients. This may improve efficiency and therefore reduce the workload. However, initially, the workload is expected to increase. This may be a hurdle for healthcare providers. We do not expect major barriers for patients, since several studies on mobile phone applications that were discussed showed good patient acceptance. Though, larger long-term studies on long-term patient adherence are

required. Also, a mobile phone application can be used to send a push notification to all patients and general instruction and educational videos can be uploaded in the app, so that patients can easily access those multiple times. This would further enhance self-management, an essential element in LVAD care. Telemonitoring may require active patient participation or could include automatic transferal of data. On the one hand, it is favorable if there is no need for active patient participation since this may lead to poor adherence and therefore reduces its potential.[44] On the other hand, by actively asking patients to participate, i.e. asking questions on symptoms, they may gain a deeper understanding of normal and abnormal situations and further improve self-care. In addition, temporarily quitting active participation in telemonitoring systems may also be predictive of deterioration. Although phone-based telemonitoring and applications were proven feasible, telemonitoring strategies can be further enriched using sophisticated algorithms for the early prediction of abnormal situations.[41]–[44]

An extensive effort is still required before algorithms can be used prospectively (figure 3). Improvement in appropriate and early notification of abnormalities without having too many alarms is needed, as alarm fatigue will hamper the successful implementation of a new monitoring strategy. Algorithms are ideally personalized and dynamic, where decisions in the trade-off between sensitivity and false alarm rate are critical. Improvements in early pump malfunction detection is a prerequisite for the success of telemonitoring in LVAD patients. Those algorithms can be improved using high-density data. Data storage on the most currently used LVADs is limited, complicating the development of prediction algorithms. A miniaturized data recorder was developed to solve this, enabling high-density pump data retrieval from HVAD. Such high density data allows us to study the mechanisms of suction and the relationship between suction and tachyarrhythmia. Even more sophisticated algorithms could make use of continuous data, with waveform analysis. Those waveforms offer much more valuable information than just average values of power, flow and PI, to estimate the left ventricle function.[31] For example, Grinsteil et al. showed that the ventricular filling phase slope of the HVAD flow waveform correlates with the pulmonary capillary wedge pressure.[38] This would also help in the development of LVAD speed control systems in the future, to reduce suction rates. Another challenge, is to monitor pump parameters online. Despite major progress in the development of algorithms, the majority is tested retrospectively and not used prospectively. Ideally, a system is developed that automatically sends pump parameters for example to a smartphone, that in turn sends it to a secured server that enables healthcare providers to assess the patient's status. Security and privacy may be at risk and should therefore be addressed appropriately, i.e. by encrypting patient data. A possible solution for security and privacy of telemonitoring data suggested by Taralunga et al. is a block chain enabled framework.[62] Another important aspect that needs to be arranged is assigning additional staff in telemonitoring centers to assess alarms and monitor LVAD patients remotely.[61] Since the implementation of telemonitoring directly results in additional costs, cost-effectiveness studies are warranted. With increasing numbers of patients on LVAD support, a regional or national monitoring center with trained personnel could filters the false alarms.

As described, most algorithms that use LVAD parameters were developed aiming to early detect PT, because it is a very severe condition and it directly affects pump parameters. Although it is a very severe condition, the incidence of pump thrombosis is very low in the contemporary LVADs.[12] Thus, we should also focus on predicting other complications. However, not all complications will be reflected by the LVAD pump parameters. Therefore, algorithms to monitor LVAD patients should not only comprise LVAD data, but also data from additional sensors, implanted devices or wearables in addition to data generated in-hospital. As technology advances, more data will be generated outside the hospital. Patients may for example not only monitor INR at home, but other biomarkers may be collected in the future using finger prick tests. In addition, we should consider focusing on blood pressure measurement and control at

home, since blood pressure is not adequately controlled in more than a third of all patients on LVAD support.[63] Combining different data sources may be challenging. A seamless incorporation with hospital patient record systems is desired, as this will save time and will improve user experience for healthcare providers, also recognized by Reiss et al.[64] An open source platform such as RADAR-base is needed. It enables the integration of data streams from various sources such as wearables, which may benefit the success of implementation.[65] Algorithms need to be developed that combine input from those different sources. Progress is being made in the development of algorithms using pump parameters. The next step is combining those pump parameters with clinical data as displayed in figure 2. In such a way, clinical decision making can be improved. Though, we should first prove the added value in larger studies. In conclusion, we strongly believe that we need to focus on the development of the infrastructure utilizing sophisticated but understandable algorithms combining different data sources, while addressing important aspects such as data safety, privacy and cost-effectiveness.

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Tables

Table 1: Complications that may occur in patients on left ventricular assist device support (LVAD), including the change in LVAD parameters and diagnosis that may, but not per se, occur.

Complication	**LVAD pump parameters**				**Diagnosis**
	Power	**Predicted Flow**	**Actual flow**	**Pulsatility index**	
Major bleeding	↓	↓	↓	↑	Hemoglobin level, endoscopy, CT-scan
Pump thrombosis	↑	↑	↓	↓	Hemolysis (serum lactate dehydrogenase 2.5 times upper limits of normal range), echocardiography, LVAD pump data
Outflow obstruction	↓	↓	↓	↓	Echocardiography, Computed Tomography scan[34], LVAD pump data
Right ventricular failure	↓	↓	↓	↑	Echocardiography, elevated central venous pressure
Arrhythmias	↓	↓	↓	↓ or ↑	Electrocardiogram
Suction	↓	↓	↓	↑	LVAD pump data
Hypertension	↓	↓	↓	↑	Blood pressure measurement
Aortic insufficiency	↑	↑	↑	↓	Echocardiography
Hemorrhagic or ischemic stroke	≈	≈	≈	≈	Computed Tomography scan
Driveline infection	≈	≈	≈	≈	Signs of infection, C-reactive Protein and culture of exit site

Figures

Figure 1: A: The left ventricular assist device and its components: inflow graft, pump, outflow graft, driveline, controller and batteries in twofold. B: In-hospital monitor. Permission for the use of those figures was granted by Abbott.

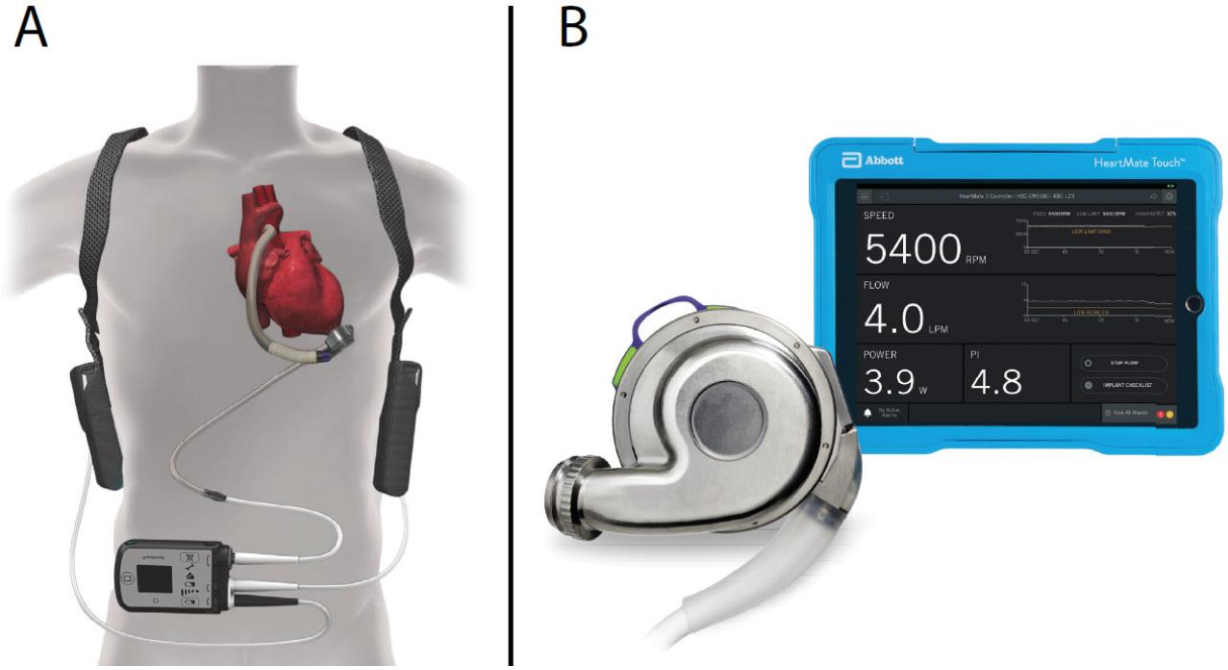


Figure 2: Aspects that can be monitored in patients on left ventricular assist device support.

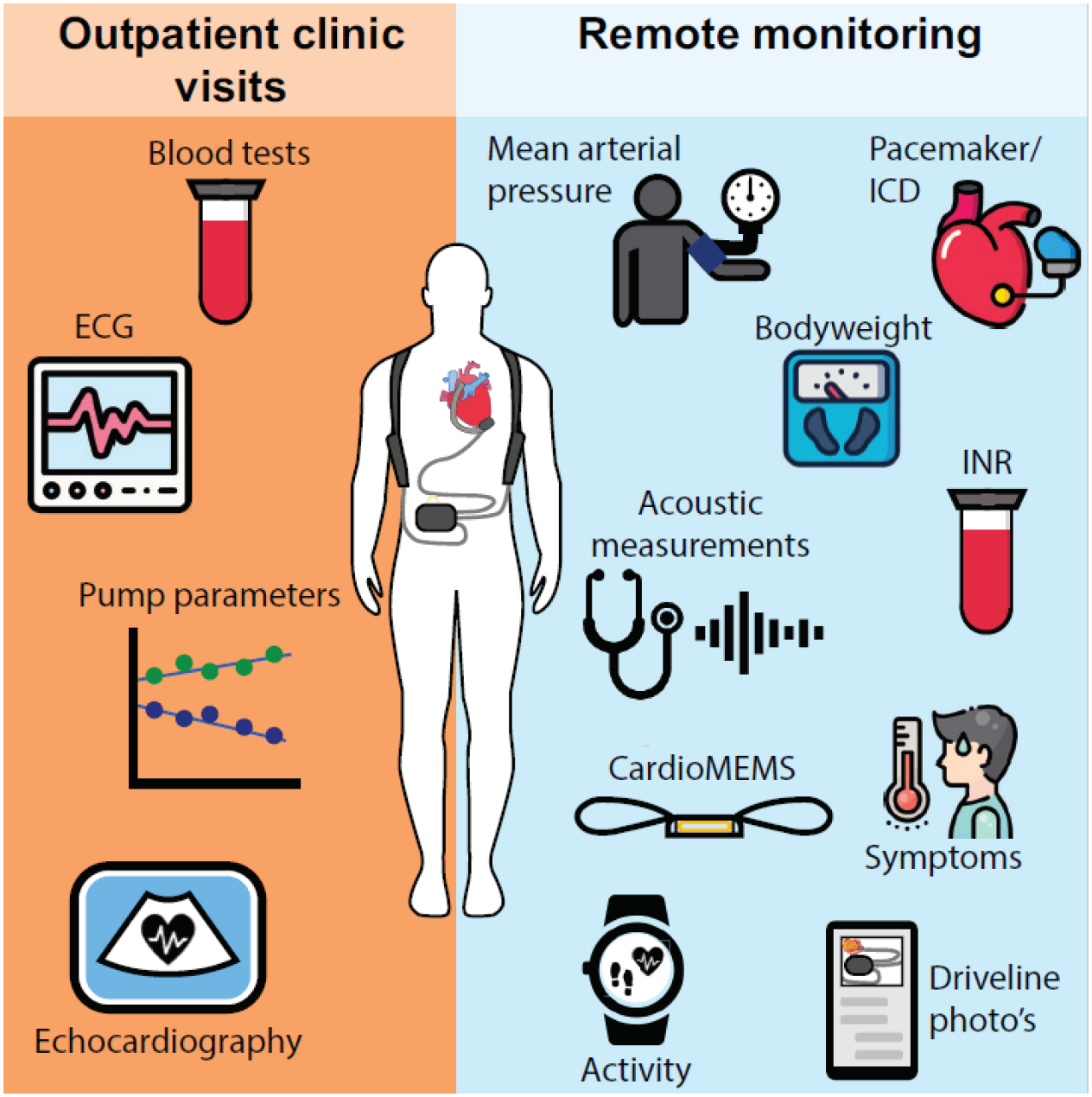
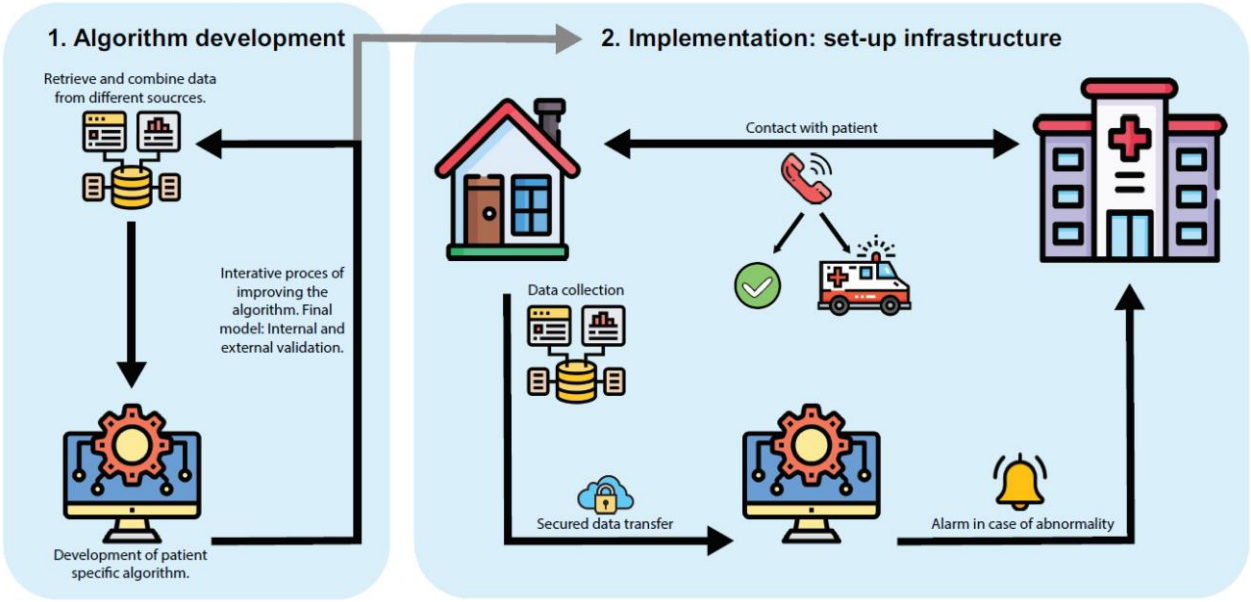


Figure 3: Steps needed before implementation and prospective usage of telemonitoring using sophisticated algorithms.



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