Title
ECG Arrhythmias and Technical Alarms during Left Ventricular Assist Device (LVAD) Therapy and its Potential Impact on Alarm Fatigue

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Publication Date
2020

Peer reviewed|Thesis/dissertation

ECG Arrhythmias and Technical Alarms during Left Ventricular Assist Device (LVAD) Therapy and its Potential Impact on Alarm Fatigue

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THESIS
Submitted in partial satisfaction of the requirements for degree of
MASTER OF SCIENCE

in

Nursing

in the

GRADUATE DIVISION
of the
UNIVERSITY OF CALIFORNIA, SAN FRANCISCO

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Dedication:

I would like to dedicate this work to my mother, Rosemary, an immigrant from Mexico that told me that I was her “American Dream”.

ECG Arrhythmias and Technical Alarms during Left Ventricular Assist Device (LVAD) Therapy and its Potential Impact on Alarm Fatigue

Kevin Watanakeeree

Abstract

Background: During alarm fatigue, true alarms can go unnoticed placing patients at risk for untoward outcomes. Patients with a left ventricular assist device (LVAD) may create challenges during electrocardiographic (ECG) monitoring due to technical alarms (i.e., artifact, ECG leads off), noise and vibrations associated with LVADs, and being able to tolerate some arrythmias. Clinical Nurse Specialists play a central role in and developing evidenced based strategies to improve alarm safety with the ultimate goal of improving patient outcomes. **Purpose/Aim:** In this case series, we analyze three patients being treated with an LVAD device in the cardiac intensive care unit (ICU) and determine: 1) the number and type of audible arrhythmia alarms; 2) the number of true versus false arrhythmias; 3) the number, type and duration of technical alarms; and 4) report alarm burden. **Methods:** Secondary analysis using data from the University of California, San Francisco (UCSF) Alarm Study. **Results:** There were a total of 547 arrhythmia alarms and 98% were false. There were 25,232 technical alarms. Of 514 total hours of ECG monitoring, technical alarms occurred for 65.9 (13%) hours. **Conclusion:** Audible arrhythmia alarms are common in LVAD patients, and the vast majority are false. Importantly, none of the arrhythmia alarms led to an untoward event (i.e., code blue or death). Technical alarms are also very common and occur for hours during routine ECG monitoring. Continuous ECG monitoring creates unique challenges in LVAD patients. Future studies are needed to explore strategies, both clinical and algorithm bases, to improve the accuracy of arrhythmia detection and minimize technical alarms in LVAD patients.

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List of Abbreviations:

AIVR: Accelerated Idioventricular Rhythm

BBB: Bundle Branch Block

CNS: Clinical Nurse Specialist

ECG: Electrocardiographic

ICU: Intensive Care Unit

LVAD: Left Ventricular Assist Device

NYHA: New York Heart Association

SPSS: Statistical Package for the Social Sciences

V-Brady: Ventricular Bradycardia

V-Tach: Ventricular Tachycardia

V-Fib: Ventricular Fibrillation

Background/Significance

Alarm safety is a National Patient Safety Goal established by The Joint Commission in 2014.[1,2] Clinical alarm systems are designed to alert busy caregivers about a change in a patient's condition to avert adverse events. While this is the goal of alarms, previous research shows that patients in the Intensive Care Unit (ICU) yield large numbers of false or nonactionable alarms (i.e. true alarms but no action needed) creating an environment for alarm fatigue. Drew et al. reported, 90% of audible arrhythmia alarms in the ICU were false.[3] In this study, and subsequent secondary data analyses, it was found that false alarms (i.e., incorrect detection of an arrythmia) were concentrated in select patients with the following characteristics including altered mental status, mechanically ventilated and in patients with certain electrocardiogram (ECG) features (i.e., bundle branch block [BBB], ventricular paced rhythms, and low amplitude QRS complexes).[3–5] We hypothesize that patients with a left ventricular assist device (LVAD) may also have high rates of false arrhythmia alarms, as well as technical alarms (i.e., artifact, ECG/Respiratory leads fail and arrhythmia suspend) due to noise and vibrations associated with LVADs. These type of patients also commonly have the ECG features known to contribute to high numbers of alarms (i.e., left BBB, ventricular pacemaker), which means LVAD patients are likely to generate high numbers of alarms and contribute to alarm fatigue.

In the study by Drew et al., it also reported of 2.5 million total alarms, 791,632 (32%) were technical alarms, which was a close second to premature ventricular complexes (n = 869,000).[3] Importantly, technical alarms may signal a problem that, if uncorrected, will lead to a complete suspension of arrhythmia detection. For example, if a technical alarm due to artifact continues, it will eventually trigger an ‘‘ARRHYTHMIA SUSPEND’’ alarm. This particular

alarm completely suspends all arrhythmia analysis, including lethal arrhythmias (i.e., asystole, ventricular fibrillation/tachycardia), placing patient's in an unsafe situation because true alarms can go undetected. Surprisingly, there are very few studies that have examined technical alarms, and to our knowledge, no studies have looked at this specifically in the LVAD patient population. The paucity of literature may exist because some technical alarms are inaudible; hence, many believe these types of alarms do not contribute to alarm fatigue. However, while some technical alarms are inaudible text messages, such as artifact, others are audible (i.e., ECG leads off, and arrhythmia suspend), which alerts the nurse to correct the problem(s). In this case series analysis study, we examine both arrhythmia and technical alarms in three LVAD patients. While this is a small study, our data could help guide clinical and algorithm-based strategies to reduce false arrhythmia and/or technical alarms in this unique patient population.

According to published data in 2019 from the American Heart Association, cardiovascular disease is the leading cause of death in the United States.[6] This same data showed that over 6.2 million people have heart failure. Heart failure is a type of cardiovascular disease and the annual total cost of cardiovascular diseases in the United States is estimated to be $351.2 billion. Patients with heart failure that worsens despite optimized medical management, along with a New York Heart Association classification (NYHA) for heart failure of IIIb to IV, are eligible for an LVAD.[7]

What is a Left Ventricular Assist Device?

When a patient with an NYHA class IV heart failure is unable to efficiently sustain optimal cardiac output, an LVAD may be implanted in the torso to support circulation. The cannula, or inlet of the mechanical device, is typically placed in the apex of the failing left

ventricle. Oxygenated blood that would normally be pumped out of the left ventricle is instead pumped out via the LVAD and routed back to the aorta in order to supply oxygenated blood to the rest of the body. [8] The power supply for the LVAD is a percutaneous driveline wire that traverses the skin and connects to the external power system. The external components of an LVAD system consist of a power source (i.e., batteries or a hard-wire power supply) and a portable controller that controls pump speed, monitors device function and has programmed alarm settings.[9] LVADs are typically categorized into two main types, pulsatile and continuous-flow, or non-pulsatile. The pulsatile LVADs were created to mimic the pulsatile nature of a native heart while the continuous flow LVAD provides steady perfusion to the body.[7] While first generation LVADs were designed as pulsatile, nearly all current devices are continuous flow (non-pulsatile). Of note, normal arterial blood pressure waveforms are typically tall, rounded and coincide with the ECG waveforms while the arterial waveform in a patient with an LVAD is flat, but still coincides with the ECG waveforms. Because patients with a non-pulsatile LVAD do not have the typical systolic and diastolic waveforms **(Figure 1),** nurses use the mean arterial pressure (MAP) to assess a patient's perfusion status. Continuous-flow devices use either a centrifugal or axial-flow pump. Both types of continuous-flow devices have a central rotor containing permanent magnets. Electrical currents running through coils cause the rotors to spin. Rotors in the centrifugal pump accelerate the blood circumferentially, producing flow toward the outer rim of the pump; rotors in the axial-flow pump are cylindrical with blades that are helical, causing the blood to be accelerated along the axis of the rotors.[7]

The physiologic condition of an end-stage heart failure patient with a non-pulsatile continuous flow LVAD is unique, in that the LVAD supports the patient's cardiac output, yet generates no discernable or palpable pulse. The phenomenon of having "no pulse" creates a

challenging situation to healthcare providers many of whom are not trained to assess and treat this unique population of patients. According to the American Heart Association,[10] in an event where resuscitation efforts may be required in an LVAD patient, emergency healthcare providers are to first assess signs of life which include mental status, ventilation, and perfusion (i.e. skin color, skin temperature, and capillary refill). This deviates from the process for non-LVAD patients, where Basic Life Support training recommends palpating for a pulse for ten seconds prior to initiating resuscitation. The second step of the American Heart Association algorithm for LVAD patients directs the healthcare provider to assess the LVAD for adequate functioning by restarting the LVAD, assessing the power supply, and auscultate for a humming sound that is generated by the LVAD. If providers are unable to troubleshoot the LVAD, chest compressions are initiated.

The U.S. Food and Drug Administration (FDA) cites two indications for LVAD reimbursement by the Centers of Medicare and Medicaid Services (CMS). First, as a bridge to transplant, which is defined as a therapy while awaiting heart transplant. Secondly, as a destination therapy, defined as ongoing therapy when the patient is unable to meet transplant requirements including age >70 years, malignancy within the past 5 years and comorbidities, chronic renal failure, drug abuse, severe obesity, and fixed pulmonary hypertension.[10,11] Studies show that there is a significant increase in survival when LVAD therapy is initiated. In the landmark REMATCH trial, which compared LVAD therapy to optimal medical therapy in patients with class IV heart failure, there was a 52% reduction in mortality among the LVAD group within the first year.[10,12] Improved mortality, along with lengthening the time from diagnosis to transplant has made LVAD therapy increasingly more popular. According to the Interagency Registry for Mechanically Assisted Circulatory Support, there have been 22,866

mechanical circulatory support devices placed between 2006 and 2016, averaging over 2,500 devices implanted per year. [13] As more LVADs are used each year, an ever-increasing body of research has emerged regarding the risks and benefits associated with these devices. As the use of LVADs increases, nurses need education about guideline-based interventions and guidance on how best to use and interpret ECG and physiologic monitoring data (i.e., blood pressure, pulse, respirations) in this patient population.

Complications associated with an LVAD device include driveline infections, strokes, gastrointestinal bleeding, circuit and pump thrombosis, and arrhythmias.[8,14–16] Factors identified as contributing to high numbers of arrhythmia events during LVAD therapy include: 1) high suction rates (decreased blood volume in the left ventricle causes the LVAD inlet to adhere to the sidewall of the left ventricle); 2) significant increases in body weight after LVAD implantation; 3) electrolyte imbalances; 4) development of myocardial scar tissue following placement; and 5) history of arrhythmias. However, because LVADs provide some degree of continuous support for cardiac output, assessment and treatment for arrythmias should be done on a case by case basis. Case reports demonstrate some LVAD patients are able to tolerate lethal arrhythmias (i.e., asystole, ventricular fibrillation [V-Fib], and ventricular tachycardia [V-Tach]) for a period of time due to the continuous blood flow produced by the LVAD.[9,17–20] However, if the arrhythmias are prolonged, patients can have deleterious symptoms and dynamic vital sign changes that require prompt identification and intervention(s).

Past studies have reported the presence of increased electrical ECG artifact and low amplitude QRS complexes associated with LVAD therapy.[16,21] Published reports indicate that some LVADs (HeartMate 3 and Heartware) create an electromagnetic field that interferes with pacemakers and ECG recordings causing 60-cycle interference.[9,22] As shown in **Figure 2**, 60-

cycle ECG interference can generate artifact alarms. **Table 1**, depicts current Practice Standards for In-hospital ECG Monitoring in patients with mechanical circulatory support, including LVADs. The practice standards identify ECG monitoring in the ICU for LVAD patients as a Class I recommendation, which means monitoring is indicated. However, we have anecdotal evidence that LVAD patients generate a high number of alarms for both technical and arrhythmia type alarms. Thus, while continuous ECG monitoring is indicated and standard practice in the ICU, the frequency of false arrhythmia and technical alarms, to our knowledge, has not been studied.

Due to their unique role in the healthcare setting, Clinical Nurse Specialists (CNS) are at the forefront of developing strategies to improve alarm safety during ECG monitoring The CNS role involves advanced knowledge in a specialty population, the ability to integrate evidence-based practice into the clinical setting, functioning as a consultant across interdisciplinary teams, and supporting nursing staff. [23] This paper is written with the CNS role in mind with the goal of providing awareness and dialogue to CNSs with regard to ECG monitoring of this unique patient population.

Purpose/Aim

As outlined above, we hypothesize that patients with an LVAD are likely to generate high numbers of false arrhythmia and technical alarms, therefore creating an environment that may foster alarm fatigue. The purpose of this case review involving three ICU patients with an LVAD device is threefold what is: 1) the frequency and accuracy of audible arrhythmia alarms for asystole, v-fib, v-tach, accelerated ventricular rhythm, ventricular bradycardia, and pause; 2) the frequency and type of technical alarms for artifact, ECG/Respiratory leads fail, and

arrhythmia suspend; and 3) the alarm burden of these two types of alarms using the numbers of alarm/hour of ICU monitoring?

Methods

Setting and Design

This is a secondary analysis of data from the UCSF Alarm Study, the methods of which have been previously published.[3] Briefly, the UCSF Alarm Study was a prospective observational study designed to examine the number and type of alarms from bedside physiologic monitors at a large tertiary-quaternary academic medical center. The technological infrastructure used in the study, captured ***all*** of the physiologic monitor data from each of the 77 ICU beds over a one-month period. A total of three types of adult ICUs were including; cardiac medical/surgical and neurological. The study was approved by the UCSF Committee on Human Research with a waiver for patient consent since all ICU patients have physiologic monitoring as part of their routine care and our data was not used for clinical care or decision making, but rather examined retrospectively. This allowed us to collect data from 461 consecutive ICU patients. For this secondary analysis, we examine three patients who had an LVAD device in place. All three patients were admitted to the cardiac ICU.

Physiologic Data Collection

All physiologic data and alarms were collected from bedside monitors (Solar 8000i; version 5.4 software, GE Healthcare, Milwaukee, WI). A research CARESCAPE Gateway system (GE Healthcare, Milwaukee, WI) was utilized to securely export the physiologic data to

an external server in order to conduct retrospective analysis (BedMasterEx; Excel Medical Electronics, Inc, Jupiter, FL). All of the available physiologic monitoring data were captured including seven lead ECG leads (I, II, III, aVR, aVL, aVF and a V lead [V1 at our hospital]), arterial blood pressure, pulse oximetry and respirations. In addition to these data we captured numeric vital signs measurements, alarm parameter settings, both audible and inaudible arrhythmia alarms, parameter violations (i.e., blood pressure too high or low) and technical alarms (i.e., artifact, ECG/Respiratory leads off and arrhythmia suspend). The technical alarms were configured in the following manner with regards to audible versus inaudible; artifact = inaudible text message; ECG/Respiratory leads fail = warning (continuous foghorn tone); and arrhythmia suspend = warning (continuous foghorn tone). Our database represents one of the largest physiologic datasets available.

Electrocardiographic Data and Annotation

Continuous ECG data was done using a five-electrode ECG lead configuration that recorded seven ECG leads (I, II, III, aVR, aVL, aVF, and V [V1 is used at our hospital]). Another unique feature of our database was that all of the 12,670 audible arrhythmia alarms were annotated as true or false, which we chose because these are more likely to contribute to alarm fatigue. The six audible arrhythmia alarms annotated were: asystole; v-fib; v-tach; accelerated ventricular rhythm; ventricular bradycardia; and pause. The annotation protocol (true vs. false) was performed by four PhD prepared nurse scientists using a standardized protocol.[3] ECG competency for each annotator was ensured by a formal 10-week ECG course each had taken and a 3-hour alarm annotation certification course taught by the principal investigator of the study. Inter-rater reliability among the annotators was 95% (Cohen's Kappa score of 0.86).

Statistical Analyses

Data were analyzed using SPSS 26.0 (IBM Corporation, 2017). Descriptive statistics were used to examine frequencies for: 1) the number and type of audible arrhythmia alarms (asystole, v-fib, v-tach, accelerated idioventricular rhythm, ventricular bradycardia, and pause; 2) the number of true and false arrhythmia alarms; and 3) the number and type of technical alarms for artifact, ECG/Respiratory leads fail and arrhythmia suspend. The values are expressed as numeric numbers and percentages. Demographics and clinical history for the three patients will not be presented in order to maintain privacy, confidentiality and meet HIPAA standards.

Results

Frequency of Arrhythmias: A total of 547 audible arrhythmia alarms occurred in the three LVAD patients. **Table 2** shows the audible arrhythmia alarms (total, type) and whether the arrhythmia was true or false. The most common type of arrhythmia alarm was for pause (n = 307; 56%) and all were false alarms. The next most common alarm was for v-tach (n = 140; 26%) and only 8 (6%) were true. **Figure 3** shows a false pause alarm. **Figure 4** shows a true v-tach alarm.

Technical Alarms: **Table 3** shows the technical alarms by type (i.e., artifact, ECG/Respiratory leads fail, and arrhythmia suspend) as well as the duration (hours). Artifact alarms were the most common and of longest duration; there were 23,427 unique alarms totaling to 22.6 hours. This was followed by ECG/Respiratory leads fail, with 854 and 821 respectively and duration 18.2 and 21.6 hours respectively. During the 514 total monitoring hours, technical alarms occurred for 66 hours (7.79%). Arrhythmia suspend (absence of arrhythmia analysis) occurred for 3.6 hours (0.7%).

Alarm Burden: The total number of monitored hours for all three LVAD patients was 514 hours. As shown in **Table 4**, the number of technical alarms/hour of monitoring far exceeded the number of arrhythmia alarms/hour of monitoring (technical 49 alarms/hours of monitoring; arrhythmia 1.06 alarms/hour of monitoring). While patient #3 had the most alarms for both arrhythmias and technical issues (n = 10,913 of 25,779; 42%), when the number of alarms/hours of monitoring is used, patient #2 had the highest number (119 alarm/hour of monitoring). This was much higher than patient #1 (54.04 alarms/hour of monitoring) and patient #3 (37.54 alarms/hour of monitoring).

Discussion

This study appears to be the first to report on audible arrhythmia and technical alarms in LVAD patients. Despite a small sample, our study illustrates the alarm burden in this specific patient population, particularly with regards to technical alarms. The six annotated arrhythmia alarms (asystole, ventricular fibrillation, ventricular tachycardia, accelerated ventricular rhythm, ventricular bradycardia, and pause) were considered clinically important enough to be set as audible and, therefore, selected for analysis. The four technical alarms (artifact, ECG Leads fail, Respiratory Leads fail, and Arrythmia suspend) were analyzed due to their association with ECG monitoring. During a one-month time period, a small number of true arrhythmias occurred (2%), with eight for v-tach and one for accelerated ventricular rhythm. None of the patients had a code blue event or died. Technical alarms were by far the most common type of alarm (98%) as compared to arrhythmia alarms, with artifact being the most common type. The overall alarm burden, measured using the number of alarms per monitored hour, was 50.15 alarms/monitored

hour. This means there was nearly one alarm every minute in these three patients, demonstrating the magnitude of alarm burden faced by nurses, LVAD patients and family members.

Of the nine true arrhythmias, eight were for v-tach and one was for accelerated ventricular tachycardia. Each of the three LVAD patients had at least one true v-tach alarm. Two of the three also had false positive v-tach, with patient #3 having the most (105 alarms). A prior investigation identified v-tach as the most prevalent arrhythmia in LVAD patients and interestingly was shown to be well tolerated in most cases.[24] Our findings supports this study in that none of the patients we examined had a code blue or rapid response call during their ICU stay. In previous studies, v-tach has been identified as an arrhythmia with a high rate of false positives and is corroborated in our study of LVAD patients.[3]

The most common arrhythmia alarm was for pause, accounting for 56% of the total number of arrhythmia alarms. We identified one reason for this was low amplitude QRS complexes (**Figure 4**). Our group has identified this ECG feature as one that leads to high numbers of false alarms especially for asystole and pause.[3–5] Patient #3, who had 77% of the total number of pause alarms, had a ventricular pacemaker; however, the "pacer-mode" feature had not been turned "on" – on the bedside monitor. This feature changes the ECG filter settings, which allows for better identification of pacer spikes and subsequent QRS detection. This one step could reduce false alarms in patients who have a ventricular pacemaker. In a prior study, we also found that not activating the pacer mode feature can lead to high numbers of false alarms for accelerated idioventricular ventricular rhythm (AIVR).[25] We did not find this in our small sample of LVAD patients since only 28 total AIVR alarms occurred, which may suggest the pacer mode feature had been turned on at some point during monitoring. This does highlight the importance of nurse education related to the pacer-mode feature for in-hospital ECG monitoring. Patient #3

was an outlier with regards to alarm frequency. This one patient had a total of 425 of the 538 (79%) arrhythmia alarms. This particular patient had both low amplitude QRSs and a ventricular pacemaker, both of which are associated with high numbers of false alarms.[3,4,25]

The most common technical alarm was for artifact, accounting for 93% of all technical alarms. Technical alarms have been cited as one of the most commonly occurring alarm in multiple studies.[3,26] While technical alarms are often configured as inaudible text message alarms, these flashing alerts can distract clinicians from patient care and contribute to alarm fatigue.[27] What our study adds is a quantification of this problem. Of the 514 total hours of monitoring in just three LVAD patients, we found that technical alarms occurred for nearly 25 hours, or 5% of monitoring. While there were substantially fewer alarms for ECG/Respiratory leads fail, the duration of these alarms was nearly that of artifact alarms (~ 20 hours). All technical alarm settings were unable to be changed or configured, therefore the factory default settings for the detection for technical alarms were used. It should be noted that these two types of alarms are configured as warning type alarms, which results in a continuous foghorn tone. This not only distracts nurses but may cause psychological anguish to patients and/or families who are already in distress.

Most notably, and quite concerning was the nearly four hours of arrhythmia suspend, which means no arrhythmia detection due to sustained artifact. This could lead to missed true arrhythmia events and highlights how persistent artifact can impact patient safety. Worth noting, unlike artifact alarms, which are inaudible text message alarms, alarms for ECG/Respiratory and arrhythmia suspend alarms were all configured as audible alarms. One can see the serious risk this might create – well intentioned nurses making adjustments to volume setting in an attempt to reduce alarm fatigue and/or distress for patients and/or families. Unfortunately, this practice

places patients at risk for missed true events. It is not surprising that interventions aimed at reducing false alarms, particularly technical alarms, have included educational interventions about proper ECG skin electrode placement, careful skin preparation, daily electrode changes along with other strategies such as customizing alarm parameters, adjust default settings for all of the monitors on a unit. [3,26,28] How these might improve false alarms specifically in LVAD patients' needs further study.

We examined alarm burden by calculating the number of alarms per hour of monitoring. There was approximately one arrhythmia alarm/hour of monitoring for all three patients. However, the alarm burden from technical alarms was much high. For all three LVAD patients, there were 49 technical alarms/hour of monitoring. Of interests, was that patient #2 had the highest alarm burden (117 alarms/hour). This patient had a great deal of 60-cycle interference during their monitoring, with an extreme example shown in Figure 3. While this particular patient did not exhibit this same pattern throughout the entire monitoring period, "fuzzy" ECG waveforms were frequent and likely explains the extraordinary number of technical alarms in this one patient. What is not known is how our number of technical alarms compare to non-LVAD patients and thus, should be examined in a future study. These data do show the high alarm burden from technical alarms experienced in LVAD patients albeit in a small sample.

Limitations

The following limitations exist for this study: small sample size, single site location, and we do not report the LVAD type. Our data came from one ECG vendor, so how these alarms might occur in a different manufacturer is not known. This secondary analysis of a small number of LVAD patients highlights the large number of arrhythmia alarms that can occur, most of

which are false, and the extreme number of technical alarms caregivers are exposed to. Because this was a secondary analysis, we were not able to explore directly the consequences of alarm fatigue on nurses (i.e., prevalence or threshold level), patients and/or families (i.e., psychological, physiological) or potential impact on patient outcomes.

Conclusion

Audible arrhythmia alarms are common in LVAD patients, and the vast majority are false. None of the three patients we included had a rapid response, code blue event, or died during hospitalization, suggesting the arrhythmia were not life threatening. While the LVAD device supports cardiac output, there is considerable risk for lethal arrhythmias and thus, identification of these events with continuous ECG monitoring is important. Resuscitation efforts differ greatly in patients with an LVAD when compared to standard Basic Life Support protocols. Therefore, education about these difference is critical. Practice Standards for In-hospital ECG monitoring state that ECG monitoring for LVAD patients treated in the ICU, is a Class I recommendations with a Level of Evidence C.[17] Given our study findings, the development of specific strategies for this specific patient group, especially with regards to technical alarms, is warranted. This secondary analysis highlights the large number of both arrhythmia and technical alarms in LVAD patients. The CNS role lends itself well to generating evidence-based practice protocols to ensure that The Joint Commission's National Patient Safety Goals for Alarm Safety are met.

This paper calls for the attention of the CNS community to be mindful of this vulnerable population. The use of LVADs is increasing hence, evidence-based solutions are needed to mitigate conditions that contribute to alarm fatigue. Future studies are needed to understand and

analyze the relationship between LVADs and alarm fatigue, which will help guide strategies to improve identification of true arrhythmias while minimizing technical alarms. Our institution has developed a special LVAD profile for use in our bedside ECG monitor. We are in the process of determining if this profile reduces false alarms (both arrhythmia and technical) while maintaining accurate identification of actionable arrhythmias.

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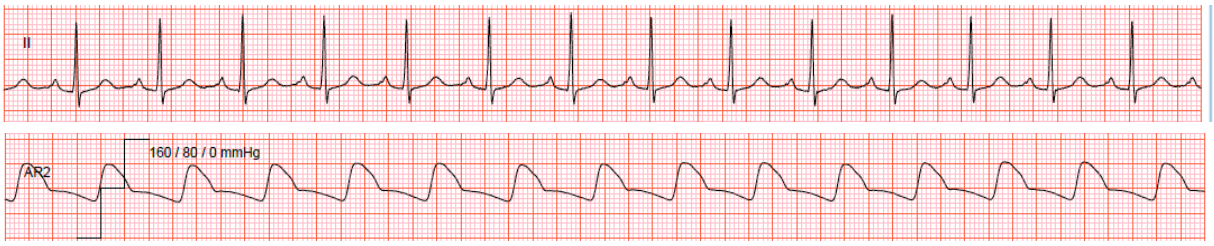
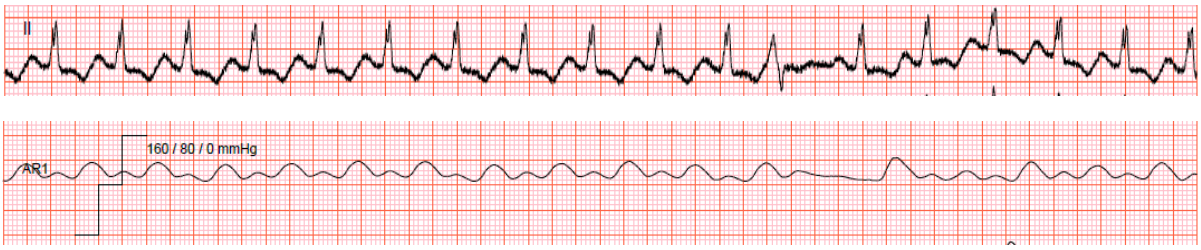


Figure 1, A and B. Illustrates an arterial blood pressure waveform in a patient without (A) and with (B) a left ventricular assist device (LVAD) along with the ECG waveform in lead II. **A.** Illustrates a normal arterial blood pressure waveform (bottom) that corresponds with the ECG waveform in lead II (top).



B. Shown is a non-pulsatile waveform (bottom) that corresponds with the ECG waveform in lead II (top) but is much smaller in amplitude as compared to Figure A (above). The mean arterial blood pressure (MAP) is used in this situation. Of note is the "fuzzy" ECG waveform, which is not uncommon in LVAD patients. Note the premature ventricular complex (7th beat from the left) with loss of the arterial blood pressure waveform after this beat.

Figure 1- Arterial Blood Monitor with and without LVAD

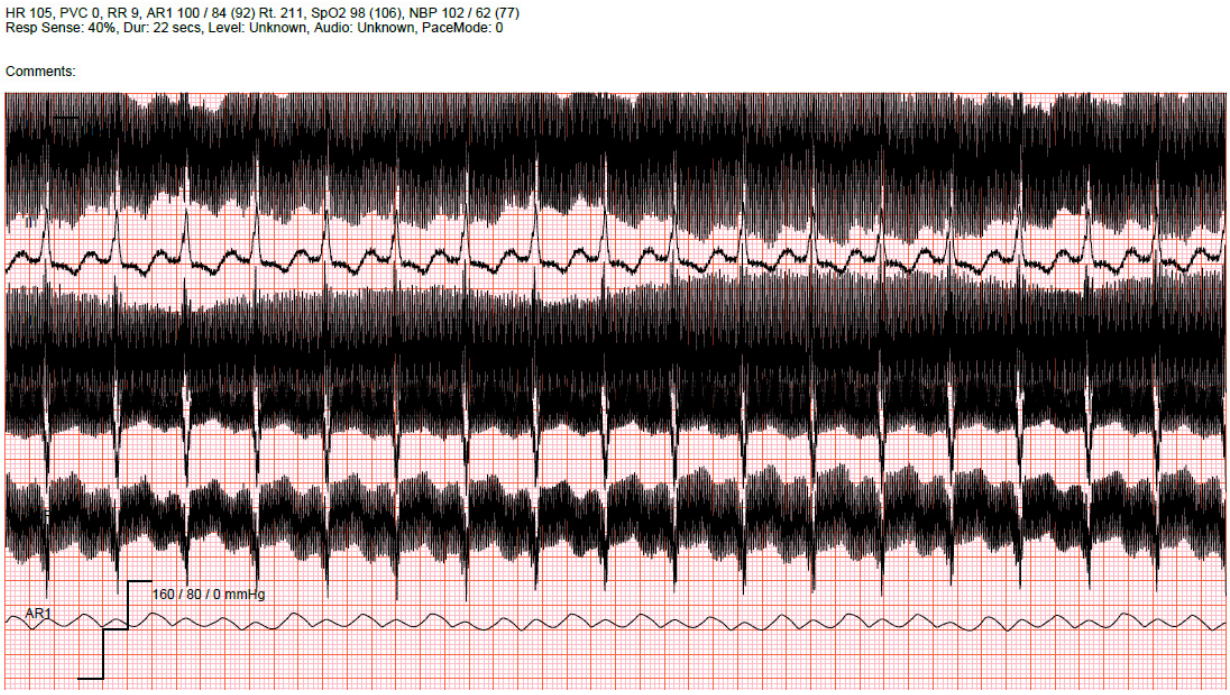


Figure 2. Example of 60-cycle interference on an electrocardiogram (ECG) obtained from the bedside monitor in a patient with a left ventricular assist device. Note the clean ECG signal in lead II, heart rate 105 beats/minute, and non-pulsatile arterial blood pressure waveform (bottom). The arterial blood pressure is 100/84 and the non-invasive blood pressure is 102/62.

Figure 2- 60 Cycle Interference from LVAD

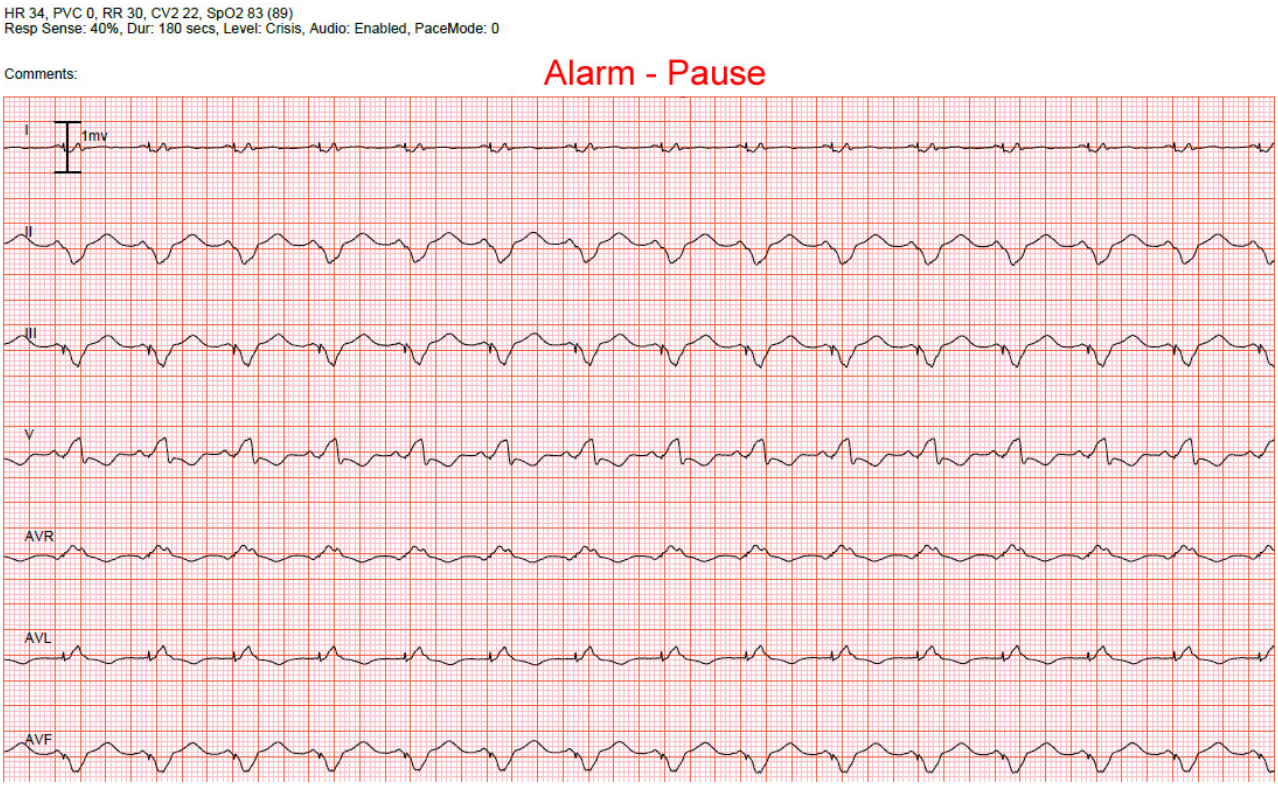


Figure 3. False pause alarm in a patient with a left ventricular assist device (LVAD). Note ventricular pacer spikes in front of every QRS complex best seen in lead III, aVL and aVF (~ 95 beats/minute). The cause of this alarm is low amplitude QRS complexes. The algorithm requires a unidirectional (only positive or negative) QRS complex > 5 millimeters in two leads, using I, II, III or V1. Note, that the pacer mode feature was not turned on (Pace mode 0), which might have reduced these types of alarms.

Figure 3-False Pause Alarm

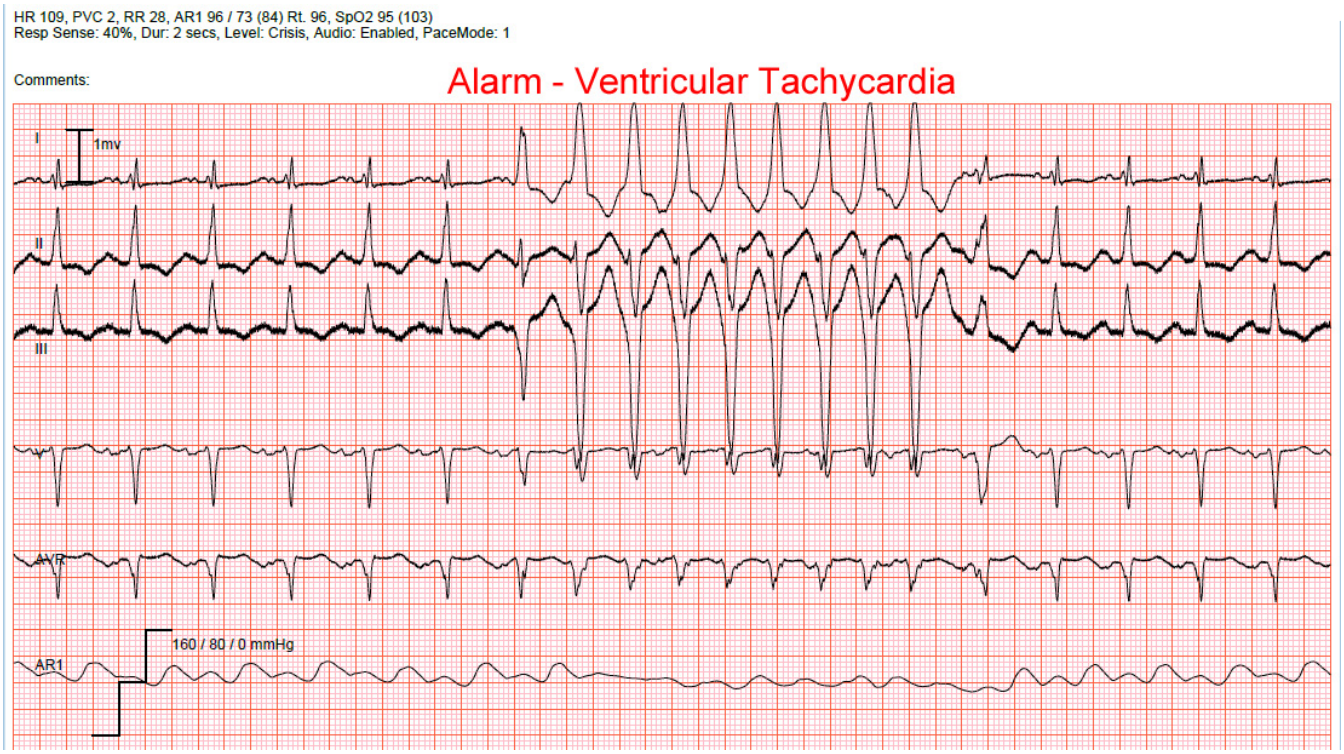


Figure 4. True ECG alarm for ventricular tachycardia. Shown are ECG leads I, II, III, V, (V1), aVR, and arterial blood pressure (AR1) in a patient with a left ventricular assist device (LVAD). Note that the non-pulsatile arterial blood pressure waveform drops during the arrhythmia, but resumes once the rhythm subsides. Also of note, is the "fuzzy" ECG waveform in leads II and III common in LVAD patients.

Figure 4-True Ventricular Tachycardia with LVAD

Table 1. Summary of current Practice Standards for In-hospital Electrocardiographic (ECG) Monitoring among patients with mechanical circulatory support, including left ventricular assist devices (LVADs).[17]

Table 1-Summary of ECG Practice Standards

Recommendation	Classification of Recommendation and Level of Evidence	Comments
1. For hemodynamically unstable patients with immediate need for mechanical circulatory support, continuous arrhythmia is indicated.	Class I; Level of Evidence C	These patients will be in the intensive care unit (ICU); hence, it is standard of care to receive ECG monitoring to allow the recognition and treatment of arrhythmias.
2. Arrhythmia monitoring is indicated for patients in the postoperative period after LVAD implantation.	Class I; Level of Evidence C	Used in the immediate post-operative period following implantation; typically treated in the ICU.
3. Arrhythmia monitoring can be beneficial for patients admitted with noncardiac problems but may not be needed in all circumstances if appropriate LVAD care can be provided.	Class IIa; Level of Evidence C	Hemodynamically stable patients admitted for non-cardiac problems (e.g., gastrointestinal bleed) will usually be treated on telemetry units. Continuous ECG monitoring is considered standard of care because many patients have a pulse that is difficult or impossible to palpate; In addition, arrhythmias may provide insight into the hemodynamics of the VAD, indicating a need to increase or decrease pump speed to optimize hemodynamic function.
4. Arrhythmia monitoring is not recommended for patients admitted to a rehabilitation facility where basic ventricular device care is available	Class III: No Benefit; Level of Evidence C	Rehabilitation facilities where staff is educated on the basic care of patients with VADs may be safe environments for these patients, even without providing continuous electrocar-diographic monitoring.

Table 2. Audible arrhythmia alarms in three patients with a left ventricular assist device (LVAD) by type and whether the arrhythmia was true or false.

V-fib = Ventricular Fibrillation; V-tach = Ventricular Tachycardia; V-brady = Ventricular Bradycardia; AIVR = Accelerated Ventricular Rhythm

Table 2-Arrhythmia alarms

LVAD Patients	Asystole		V-Fib		V-Tach		V-Brady		AVR		Pause		Total Alarms	
	True	False	True	False	True	False	True	False	True	False	True	False	**True**	**False**
#1	0	3	0	0	3	0	0	0	0	0	0	2	3	5
#2	0	11	0	0	2	27	0	0	0	1	0	69	2	108
#3	0	45	0	2	3	105	0	10	1	27	0	236	4	425
Total = 547	0	59	0	2	8	132	0	10	1	28	0	307	9	538

Table 3. Illustrates the type, number, and length (minutes) of technical alarms in patients with a left ventricular assist device

Table 3- Technical Alarms

LVAD Patient	Monitor Hours	Artifact		ECG Leads Fail		Respiratory Leads Fail		Arrhythmia Suspend		Total Alarms	
		Number	Hours	Number	Hours	Number	Hours	Number	Hours	Number	Hours
#1	182	9,395	8.3	208	4	201	4	32	0.7	9,836	16.8
#2	42	3,925	3.2	483	2.3	461	5.7	43	1.7	4,912	12.9
#3	290	10,107	11	163	12	159	12.1	55	1.1	10,484	36.3
Total	514	23,427	22.6	854	18.2	821	21.6	130	3.6	25,232	65.9

Table 4. Alarm burden calculated for three left ventricular assist device (LVAD) patients using the number of alarms divided by the hours of monitoring.

Table 4- Alarm burden

LVAD Patient	Monitoring Hours	Arrhythmia		Technical		Total Alarms	
		# of arrhythmia alarms	# of alarms/hour of Monitoring	# of technical alarms	# of alarms/hour of Monitoring	All alarms	# of alarms/hour of monitoring
#1	182	8	0.04	9,836	54	9,844	54.04
#2	42	110	2.6	4,912	116.7	5,022	119.3
#3	290	429	1.47	10,484	36.1	10,913	37.57
Total	514	547	1.06	25,232	49	25,779	50.15

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