Intensive Care Med
https://doi.org/10.1007/s00134-024-07382-y

CONFERENCE REPORTS AND EXPERT PANEL

British societies guideline on the management of emergencies in implantable left ventricular assist device recipients in transplant centres

Waqas Akhtar[1,2*], Veronica Rial Baston[3], Marius Berman[4], Sai Bhagra[4], Colin Chue[5], Charles D. Deakin[6], Jonathan R. Dalzell[3], Joel Dunning[7], John Dunning[1], Roy S. Gardner[3,8], Kristine Kiff[1], Shishir Kore[9], Sern Lim[5], Guy MacGowan[10], Ian Naldrett[11], Marlies Ostermann[12], Sofia Pinto[1], Stephen Pettit[4], Fernando Riesgo Gil[1], Alex Rosenberg[1], Antonio Rubino[4], Rana Sayeed[13], Joao Sequeira[4], Neil Swanson[14], Steven Tsui[13], Christopher Walker[15], Stephen Webb[12], Andrew Woods[10], Rajamiyer Ventkateswaran[9,13] and Christopher T. Bowles[1]

Abstract

An implantable left ventricular assist device (LVAD) is indicated as a bridge to transplantation or recovery in the United Kingdom (UK). The mechanism of action of the LVAD results in a unique state of haemodynamic stability with diminished arterial pulsatility. The clinical assessment of an LVAD recipient can be challenging because non-invasive blood pressure, pulse and oxygen saturation measurements may be hard to obtain. As a result of this unusual situation and complex interplay between the device and the native circulation, resuscitation of LVAD recipients requires bespoke guidelines. Through collaboration with key UK stakeholders, we assessed the current evidence base and developed guidelines for the recognition of clinical deterioration, inadequate circulation and time-critical interventions. Such guidelines, intended for use in transplant centres, are designed to be deployed by those providing immediate care of LVAD patients under conditions of precipitous clinical deterioration. In summary, the Joint British Societies and Transplant Centres LVAD Working Group present the UK guideline on management of emergencies in implantable LVAD recipients for use in advanced heart failure centres. These recommendations have been made with a UK resuscitation focus but are widely applicable to professionals regularly managing patients with implantable LVADs.

Keywords: LVAD, Cardiac arrest, Resuscitation, Mechanical circulatory support, Heart failure

Introduction

A ventricular assist device (VAD) is a mechanical blood pump which replaces or supplements native ventricular function. This article pertains specifically to recipients of implantable (long-term) continuous flow left ventricular assist devices (LVAD).

LVADs are deployed as treatment for advanced heart failure in patients who are refractory to medical therapy. In the United Kingdom (UK), implantable VADs are commissioned at six adult cardiothoracic centres as a bridge to transplantation or native heart recovery [1]. They are typically implanted when no suitable donor heart can be found due to time constraints, or in the presence of elevated human leukocyte antibody levels and donor size matching issues. They can also be used as a bridge to candidacy or decision such as when there is a contraindication to heart

*Correspondence: waqas.akhtar@nhs.net
[1] Harefield Hospital, London, UK
Full author information is available at the end of the article

Springer

transplantation (e.g. pulmonary hypertension) that is anticipated to be reversible using LVAD therapy.

The current generation of LVADs are centrifugal blood pumps comprising a rotating impeller which is levitated by either magnetic forces alone (Heartmate III, Abbott Inc., Chicago, United States of America (USA)) or a combination of magnetic and hydrodynamic forces (HeartWare Ventricular Assist Device (HVAD) system, Medtronic Inc., Minneapolis, USA) (Fig. 1). The LVAD inflow is connected to the left ventricular apex and its outflow to the ascending aorta. Electrical power is provided to the implanted pump via a percutaneous driveline cable which is connected to an external controller that receives power from rechargeable batteries or a mains transformer.

Under conditions of a constant pressure gradient across the LVAD and a fixed impeller rotation rate, rotary LVADs generate steady (continuous) blood flow from the left ventricle to the systemic circulation. Normally, however, the left ventricle continues to contract during LVAD support which induces a decrease in the pressure difference across the LVAD and a corresponding increase in LVAD flow resulting in an attenuated arterial blood pressure pulse. In combination, these effects result in a unique state of haemodynamic stability with diminished arterial pulsatility. Consequently, the clinical assessment of an LVAD recipient can be challenging because accurate non-invasive blood pressure, pulse and oxygen saturation may be hard to obtain, particularly under conditions of clinical deterioration, though may still be possible [2].

LVAD therapy can confer haemodynamic stability for prolonged periods and technological improvements have reduced the rate of LVAD-associated complications. However, patients undergoing contemporary LVAD therapy remain at unacceptably high risk of life-threatening complications, notably infection, bleeding and stroke [3, 4]. As recently as 2017, after one year of LVAD therapy, 93% of patients had an adverse clinical event including issues with haemocompatibility related adverse events, infection, right ventricular failure and aortic regurgitation [5]. When cardiac arrest occurs in LVAD recipients, the mortality rate is over 60% [6]. The combination of a lack of reliable clinical signs and high risk of complications makes LVAD recipients very vulnerable, particularly if the need for resuscitation arises. Moreover, there is a historical view that cardiopulmonary resuscitation (CPR) is unsafe in LVAD recipients which is not supported by the limited published data [7, 8]. This uncertainty has been shown to both delay the initiation of CPR and limit its application.

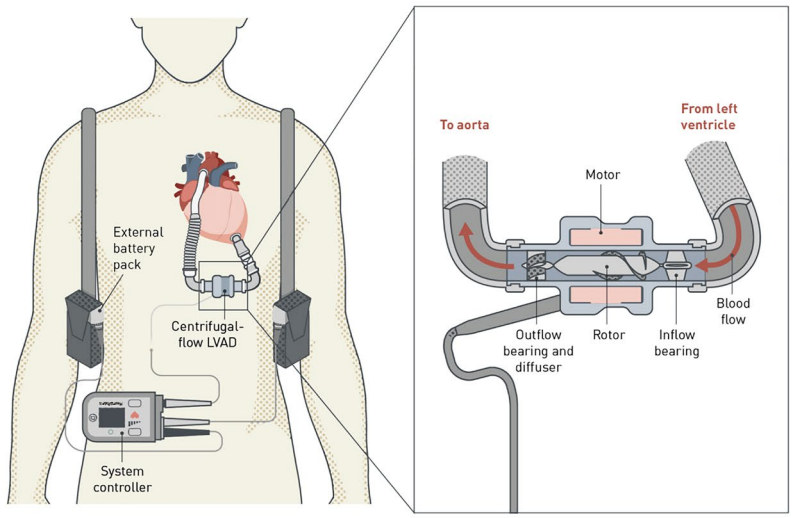
Various bespoke LVAD-specific CPR algorithms and protocols have been proposed for use by staff working in advanced heart failure centres [9–12]. International organisations have also included recommendations in society statements and guidelines [13, 14]. All of the proposed models have their merits, yet may vary in their effectiveness according to how well-targeted they are towards staff groups sufficiently skilled to interpret and implement them. In the UK, first responders to in-hospital emergencies are typically bedside nursing staff and junior doctors who may not have adequate experience of dealing with such a complex situation.

Advanced Life Support (ALS) courses and literature provided by the Resuscitation Council UK have protocolised emergency care in non-LVAD patients in a manner which can be readily utilised by these first responders [15]. In this guideline we sought to provide a clear guidance for first responders to deteriorating LVAD recipients with particular emphasis on the recognition of arrest, initiation of CPR and key early interventions that can impact outcomes. These guidelines have been made with a UK-based resuscitation focus but are widely applicable to appropriately trained clinicians regularly managing patients with implantable LVADs.

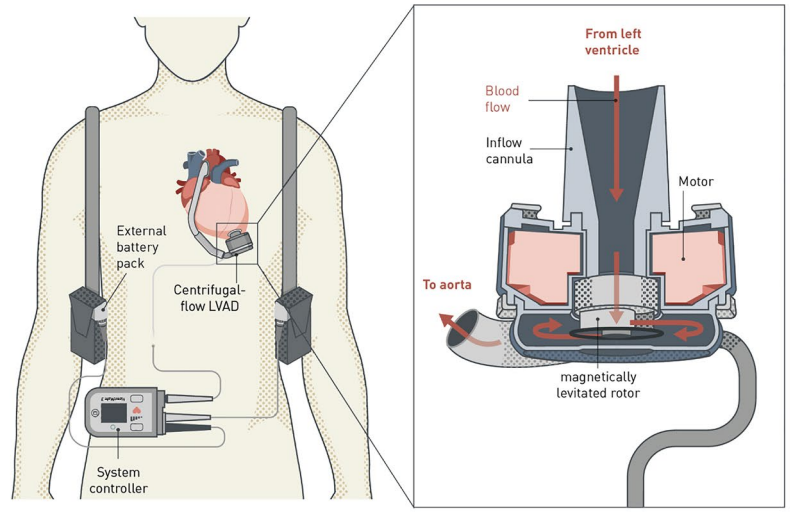
Scope and methods

The guideline is designed for staff in advanced heart failure centres in the United Kingdom that manage adult patients with implantable LVADs. Specifically, this relates to emergencies with any of the following implantable LVADs currently in use to treat adults: the Medtronic Inc HVAD, Minneapolis, USA and Abbott Inc Heartmate II & III, Chicago, USA systems. Existing national guidance is in place for the emergent management of these patients in the outpatient setting primarily for the benefit of ambulance clinicians [16]. This guideline is intended to be complementary and implemented through the provision of structured training [9].

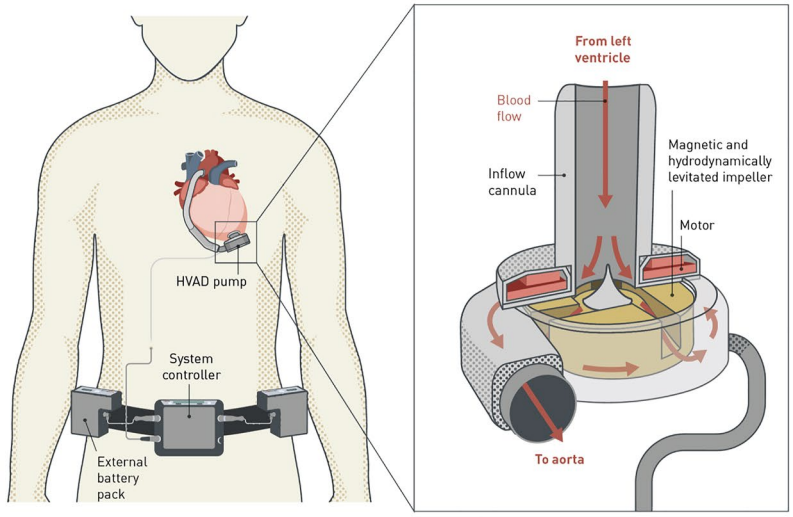
We developed this guideline by convening a national LVAD Emergency Algorithm Working Group comprising 14 key UK stakeholder groups: the six advanced heart failure centres where implantable LVADs are implanted: Freeman Hospital, Newcastle, Golden Jubilee National Hospital, Glasgow, Harefield Hospital, London, Royal Papworth Hospital, Cambridge, Wythenshawe Hospital, Manchester and Queen Elizabeth Hospital, Birmingham. The process was supported by eight national organisations: Association of Cardiothoracic Anaesthesia and Critical Care, British Association of Critical Care Nurses, British Cardiovascular Society, British Society of Heart Failure, Intensive Care Society, Faculty of Intensive Care Medicine, Resuscitation Council UK, and the Society for Cardiothoracic Surgery in Great Britain and Ireland. All conflicts of interest (COI) were identified and declared; the chair was required to have no direct COI. Any member with a direct financial COI was not eligible to decide on strength of recommendation relating to the COI.



Heartmate II



Heartmate III



Heartware Ventricular Assist Device (HVAD)

Fig. 1 Current left ventricular assist devices

Evidence was collected from MEDLINE and Google Scholar from 2000 onwards pertaining to LVAD relevant guidelines and articles addressing: initial response to cardiac arrest, responder teams, LVAD troubleshooting, assessing adequacy of circulation in LVADs and cardiac arrest in LVADs. Selected search terms included LVAD and; cardiac arrest, resuscitation, CPR, emergencies, algorithm, alarms, ventricular arrhythmias, extracorporeal membrane oxygenation (ECMO), Impella. A narrative summary of the evidence was tabulated and made available to the expert panel (see Supplementary Appendix A). The European Society of Cardiology framework for guidelines was used to determine the class of recommendation and level of evidence [17]. This details a standard process for membership formation and declaration of COI. A quorate 75% agreement was required for a level of recommendation. The class of recommendation is as follows; I is recommended, IIa is should be considered, IIb is maybe considered, III is not recommended. The level of evidence is as follows; A refers to multiple randomised trials, B to a single randomised trial, C to observational data and expert consensus.

Through the working group a modified Delphi process was used to develop consensus by means of majority. A vote was assigned to each advanced heart failure centre and each national society, with the consortium chair deciding a split vote. The consultation process was initiated in September 2022 with formation of the working group in January 2023. Through electronic communications, virtual meetings and after eight modified Delphi rounds, the following guideline was finalised in December 2023.

UK LVAD emergency algorithm development

Key issues were considered sequentially by the working group, as detailed below.

Recommendation	Class	Level
Emergency responders to patients deteriorating and in cardiac arrest with left ventricular assist devices are recommended to have dedicated resuscitation training using a structured algorithm	I	C

Initial response

We recommend placing an immediate cardiac arrest call if any LVAD recipient is found unresponsive and/or not breathing normally. Cardiac arrest calls can also be placed for any deteriorating LVAD recipient and/or where a staff member is concerned and if there are delays in contacting specialist help. In some advanced heart failure centres, activation of an "LVAD cardiac arrest call" will lead to the 24/7 on-call specialist VAD nurse being contacted who can provide prompt expert guidance. In UK hospitals cardiac arrest team activation is through a standardised phone number "2222", which we were therefore incorporated into this national algorithm.

We debated the timing of CPR extensively during the process of design and testing of the algorithm. There are surgical concerns around a risk of anastomotic rupture during chest compressions as the LVAD outflow graft lies in close proximity to the sternum. However, the limited evidence available suggests this risk may have been overestimated particularly in the late post-operative phase [6–8]. The dominant issue is the fact that contemporary rotary LVADs have a non-occlusive (valve-less) blood path. Thus, when the LVAD stops working, retrograde blood flow can occur from the aorta via the non-functional LVAD, into the left ventricle. The retrograde LVAD flow not only compromises systemic (and hence cerebral) perfusion, particularly if residual left ventricular function is very poor but also limits the efficacy of CPR. However, despite these limitations, in the face of persistent LVAD failure, CPR would be expected to augment systemic perfusion, albeit to a limited extent. Thus, we recommend a delay of a maximum of 2 min whilst attempting to restore LVAD function (which is the most effective resuscitative tool available) prior to the initiation of CPR.

Recommendation	Class	Level
In the event of LVAD failure and cardiac arrest, CPR may be deferred for a maximum of 2 min while immediate interventions are made to restore device function	IIa	C

Initial and secondary responder

If a single responder is present, the priority after calling for help should be to diagnose and promptly treat LVAD dysfunction, if possible. This is equivalent to early CPR in standard life support. This change in focus from resuscitating the patient to restarting the machine addresses the importance of a functioning pump as the best chance of restoring adequate circulation in device dysfunction. The second responder, who normally will arrive promptly in the hospital setting, should focus on the standard 'Airway' then 'Breathing' approach to patient assessment and attach electrocardiographic monitoring as part of the 'Circulation' step.

Recommendation	Class	Level
The recommended priority in LVAD cardiac arrest is to restore circulation by resolving device dysfunction caused by mechanical failure or physiological problems	I	C

LVAD troubleshooting

The first action of the initial responder, after calling for help, is to review the information displayed on the LVAD controller screen to guide subsequent actions. LVADs have a range of visual hazard advisories which are displayed on the controller and are accompanied by various audible alarms. These allow the patient/staff to distinguish between low, medium and high priority alarms [18, 19]. We have specified alarms according to the screen text display that could potentially be associated with a resuscitation episode to guide lifesaving interventions.

Blank controller

This can be a normal operational state of the Heartmate III LVAD so the initial step is to depress any button on the controller to activate the screen. If the screen of either the Heartmate III or HVAD continues to be blank after a button is depressed, the LVAD is either (a) completely depleted of power and must be connected to a functional power source, or (b) controller has failed and must be replaced.

High pump power (Watts)

This can be indicative of the presence of a thrombus within the pump which impinges between the rotating impeller and the pump housing and will require confirmation by blood tests (plasma haemoglobin and lactate dehydrogenase), LVAD log file analysis, and echocardiography. Based on these findings, a clinical management plan can subsequently be devised. If the pump thrombosis episode is associated with inadequate circulation, immediate temporary mechanical circulatory support e.g. veno arterial ECMO (VA-ECMO) or salvage thrombolytic therapy may be considered.

Driveline disconnection

The percutaneous LVAD driveline may have become disconnected and will need to be reconnected to the controller. Alternatively, the driveline may have a modular component (Heartmate III) that has become disconnected. Consequently, exposure of the entire driveline is mandatory to allow observation of such a disconnection. A third possibility is driveline fracture from mechanical fatigue or damage, which, if detected, should be managed by gentle manipulation to try and restore electrical continuity. If this manoeuvre is successful, the driveline should be immobilised temporarily with adhesive tape until specialist engineering support can be provided. If the driveline is completely severed, there is no simple remedial intervention to restore electrical continuity.

Low or critical battery

This requires replacement of a rechargeable battery with a charged battery or connection of the controller to mains power.

Low flow alarm

For the HVAD and Heartmate II and III, blood flow rate is not directly measured but is estimated from LVAD electrical power consumption and blood viscosity using either the haematocrit or packed cell volume as a surrogate. For a given impeller rotation rate, the blood flow generated by the LVAD is inversely proportional to the pressure difference across the LVAD, i.e. aortic minus left ventricular pressure. Thus, paradoxically, relative hypotension is desirable in LVAD recipients because it is associated with the preservation of adequate LVAD blood flow which not only assures adequate perfusion but minimises the risk of thrombogenesis in the LVAD. This is best achieved through maintenance of mean arterial blood pressure (MAP) in the 60–80 mmHg range. A low LVAD blood flow alarm is likely to be caused by inadequate LVAD filling, the most common cause being hypovolaemia [20] which is frequently attributable to dehydration or more rarely, bleeding (e.g. gastrointestinal). The primary intervention in response to suspected hypovolaemia should be a passive leg raise, which, if effective, can be followed by cautious intravenous fluid administration (e.g. 4 ml/kg) targeting a MAP above 60 mmHg [21]. Haemorrhage management requires an individualised balanced approach with due consideration of the severity of bleeding and risk of pump thrombosis [22]. In severe bleeding or that occurring in sensitive compartments, such as the brain, reversal of anticoagulation is almost always indicated. In the case of haemorrhagic cardiac arrest a standardised major haemorrhage protocol with balanced transfusion and reversal of coagulation with specific agents or blood products is necessary.

An alternative cause of a low LVAD flow alarm is right ventricular failure, to which further fluid administration could be detrimental. The recognition of right ventricular failure will require historical review of investigations such as echocardiography and right heart catheterisation data. In the immediate setting, echocardiography is likely to be the most rapid route to diagnostic assessment. If available, invasive monitoring such as significantly elevated central venous pressure or pulmonary artery catheter data can also support diagnosis of a volume overloaded state and the subsequent avoidance of intravenous fluid administration.

The low flow alarm can also be activated in response to an excessive LVAD afterload. If the peripheral or invasive MAP > 90 mHg and alternative causes of low flow above are assessed and excluded, antihypertensive medication should be administered such as intravenous hydralazine, sodium nitroprusside or glyceryl trinitrate.

A rarer cause of low flow is a restriction to blood flow within the LVAD blood path, e.g. thrombus or a partially occluded LVAD inflow/outflow. It is managed in a similar

manner to pump thrombosis which impinges between the impeller and pump housing resulting in a refractory LVAD power increase. A low flow alarm may also occur because of torsion, compression or kinking of the LVAD outflow graft. This requires surgical correction.

Arrhythmias can also trigger low flow alarms, either through left ventricular preload reduction and/or left ventricular cavity obliteration (a suction event).

Recommendation	Class	Level
In an unwell adult patient with "low flow" alarm a passive leg raise should be considered and if responsive a fluid bolus of 250 ml or 4 ml/kg delivered. Available echo, Doppler blood pressure and invasive parameters should be assessed for right ventricular failure and excess afterload where fluid would not be of benefit	IIa	C

Ventricular arrhythmias

Although ventricular arrhythmias are associated with poor outcomes in LVAD recipients, they may be well-tolerated in the short term due to maintenance of perfusion by the LVAD [23]. This can result in a patient retaining cerebral responsiveness despite ventricular tachycardia (VT) or ventricular fibrillation (VF). In the presence of an adequate circulation, chemical cardioversion can be attempted in VT. Patients are also likely to have implantable cardioverter defibrillators which can be used to deliver anti-tachycardia pacing. If the VT rate falls below programmed detection boundaries, then the VT zone can be reprogrammed by the pacing team to deliver this therapy.

When electrical cardioversion or defibrillation is being considered, sedation must be implemented if patient shows signs of consciousness. Contemporary LVADs are not susceptible to damage from defibrillation or cardioversion. Antero-posterior pad positioning is preferred as the LVAD is connected to the left ventricular apex and is likely to lie in the antero-lateral pad vector although this is not invariably the case.

If there is inadequate circulation and the patient is unresponsive, then defibrillation should be implemented without delay with three stacked shocks, if required.

Recommendation	Class	Level
In ventricular fibrillation or ventricular tachycardia, defibrillation or cardioversion is recommended to be delayed if patient shows any signs of consciousness until sedation can be implemented	I	C

Determination of adequacy of circulation

After LVAD troubleshooting has been attempted and VF/VT has been treated, the adequacy of circulation should be confirmed. LVAD recipients with a normal circulation will be responsive, not centrally cyanosed, have a normal capillary refill (< 3 s), MAP > 60 mmHg [21] and have a normal end tidal carbon dioxide ($ETCO_2$); which we have defined as being > 2 kPa in an intubated patient in accordance with other published CPR guidelines [13]. Ultimately, the LVAD should have a normal controller display without active audible and visual alarms, typically with a flow rate > 3 L/min in adults. LVAD hum should be audible on auscultation of the chest.

If there is adequate circulation, staff should undertake a standard 'Airway, Breathing, Circulation, Disability, Exposure' assessment. A persistent reduction in the level of consciousness and/or respiratory arrest in spite of an adequate circulation is strongly suggestive of an acute neurological event, e.g. stroke [21]. Patients in a low cardiac output state, with borderline adequacy of circulation should be considered for inotropic infusions to increase intrinsic cardiac output although excessive vasoconstriction should be avoided as an elevated systemic vascular resistance limits LVAD flow.

If the circulation remains inadequate, high-level specialist expertise is required. Although the parameters of adequacy of circulation can be assessed, clinical judgement is imperative in the LVAD recipient. We chose not to be prescriptive as even potentially reliable parameters, such as $ETCO_2$, may not be failsafe, for example, in the case of a loose-fitting facemask or laryngeal mask airway. If the patient is within 10 days of LVAD implantation, the Cardiac Advanced Life Support (CALS) algorithm should be followed [24] with chest reopening, if indicated.

In the absence of a Do Not Attempt Resuscitation (DNAR) order and following confirmation of inadequate circulation, CPR should be started either with a view to replacement mechanical circulatory support system or to maintain circulation during assessment and treatment of 4Hs (Hypoxia, Hypothermia, Hypovolaemia, Hyper/Hypokalaemia) and 4Ts (Thrombosis, Toxins, Thromboembolism Tension pneumothorax) according to ALS guidance such as thrombolysis for pump thrombosis [25].

Replacement devices include the Abiomed Inc. Impella (Danvers, USA), VA-ECMO or another implantable LVAD. Randomised evidence for emergency ECMO initiation in out-of-hospital cardiac arrest (non-LVAD related)

(See figure on next page.)

Fig. 2 UK LVAD emergency algorithm. *LVAD* left ventricular assist device, *ECG* electrocardiograph, *MAP* mean arterial pressure, *GI* gastrointestinal, *Hb* haemoglobin, *DC* direct current, *ETCO2* end-tidal carbon dioxide, *A to E* airway to exposure, *GCS* Glasgow Coma Score, *CPR* cardiopulmonary resuscitation, *ALS* advanced life support

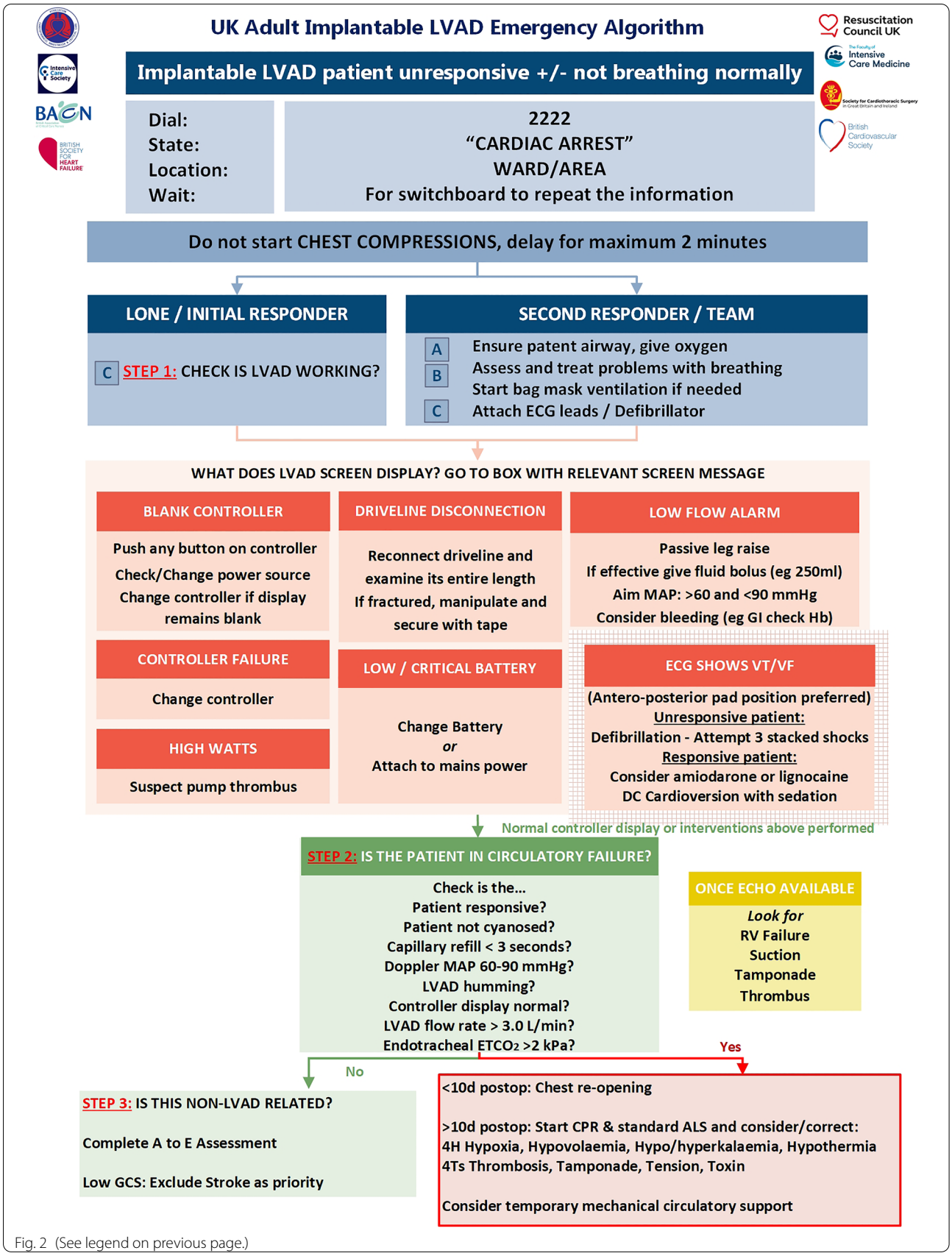


Fig. 2 (See legend on previous page.)

is well established and ECMO flow should be initiated within 60 min of the onset of arrest [26, 27]. Temporary mechanical circulatory support presents technical challenges including retrograde flow through the dysfunctional LVAD which may require outflow graft occlusion device, e.g. an Abbott Inc Amplatzer (Chicago, USA).

Mechanical CPR devices are associated with a lack of reliable safety data in LVAD recipients [28]. Pragmatically they have a demonstrated role in prolonged cardiac arrest and during the institution of emergency ECMO. Mechanical CPR is unadvisable in certain high risk patient groups such as those with chest wall deformities and elderly women [29].

Echocardiography can be of utility in determining the cause of cardiac arrest, such as right ventricular failure, suction events, tamponade, or intracardiac thrombus. However, it is reliant on a competent sonographer being available at the time of the emergency and acoustic windows may be limited. Thrombus within the LVAD pump housing cannot be visualised by echocardiography and so this remains an adjunctive investigation in our algorithm rather than a treatment-determining criteria.

Importantly patients with LVADs who require CPR have a very poor outcomes [6] which raises ethical questions around whether management should focus allowing death with dignity rather than administering extreme interventions. These are considerations that should be discussed with patients when they are well enough to consider their wishes and should be written into advanced care and treatment escalation plans.

Recommendation	Class	Level
Assessment of adequate circulation is recommended to be made utilising a number of physiological parameters and not pulse alone	I	C
CPR can be performed safely in LVAD patients with inadequate circulation	IIa	C
The use of mechanical CPR devices in LVAD patients is lacking safety data and should only be considered in refractory arrests and to facilitate emergency ECMO insertion	IIa	C
In the presence of inadequate circulation in a LVAD patient less than 10 days post LVAD implantation, emergent chest re-opening should be considered if initial measures have failed	IIa	C
In the presence of inadequate circulation immediate escalation to temporary mechanical support such as ECMO should be considered and initiated within 60 min	IIa	C

Conclusion

Figure 2 illustrates the output from this initiative, i.e. an implantable LVAD-specific resuscitation guideline for in-hospital use in specialist advanced cardiac centres. This guideline is intended to be implemented in combination with a structured training programme and has been endorsed by all UK transplant centres and national societies contributing to this work. This guideline outlines a pragmatic approach for frontline healthcare staff for the recognition of clinical deterioration, prioritisation of time critical interventions and decision making on the initiation of CPR.

Supplementary Information
The online version contains supplementary material available at https://doi.org/10.1007/s00134-024-07382-y.

Author details
[1] Harefield Hospital, London, UK. [2] Faculty of Intensive Care Medicine, London, UK. [3] Golden Jubilee National Hospital, Glasgow, UK. [4] Royal Papworth Hospital, Cambridge, UK. [5] University Hospitals Birmingham, Birmingham, UK. [6] Resuscitation Council UK, London, UK. [7] Cardiac Advanced Resuscitation Education, Festus, MO, USA. [8] British Society of Heart Failure, London, UK. [9] Wythenshawe Hospital, Manchester, UK. [10] Freeman Hospital, Newcastle, UK. [11] British Association of Critical Care Nurses, Newcastle, UK. [12] Intensive Care Society, London, UK. [13] Society for Cardiothoracic Surgery in Great Britain & Ireland, London, UK. [14] British Cardiovascular Society, London, UK. [15] Association of Cardiothoracic Anaesthesia and Critical Care, London, UK.

Declarations

Conflicts of interest
There are no direct conflicts of interest for this paper; see ICJME declaration for all other statements.

Publisher's Note

Received: 26 December 2023 Accepted: 29 February 2024
Published online: 25 March 2024

References

1. Parameshwar J, Hogg R, Rushton S et al (2019) Patient survival and therapeutic outcome in the UK bridge to transplant left ventricular assist device population. Heart 105:291–296. https://doi.org/10.1136/HEARTJNL-2018-313355
2. Lankheet S, Pieterse MM, Rijnhout R et al (2022) Validity and success rate of noninvasive mean arterial blood pressure measurements in cf-LVAD patients: a technical review. Artif Organs 46:2361–2370. https://doi.org/10.1111/AOR.14367
3. Mehra MR, Uriel N, Naka Y et al (2019) A fully magnetically levitated left ventricular assist device—final report. N Engl J Med 380:1618–1627. https://doi.org/10.1056/NEJMOA1900486

4. Kirklin JK, Naftel DC, Kormos RL et al (2013) Fifth INTERMACS annual report: risk factor analysis from more than 6,000 mechanical circulatory support patients. J Heart Lung Transplant 32:141–156. https://doi.org/10.1016/J.HEALUN.2012.12.004
5. Lohmueller LC, Movahedi FA, Antaki JF (2017) Living the dream: event free survival in patients receiving a Cf-LVAD. J Card Fail 23:S118. https://doi.org/10.1016/j.cardfail.2017.07.347
6. Barssoum K, Patel H, Rai D et al (2022) Outcomes of cardiac arrest and cardiopulmonary resuscitation in patients with left ventricular assist device; an insight from a national inpatient sample. Heart Lung Circ 31:246–254. https://doi.org/10.1016/J.HLC.2021.05.096
7. Mabvuure NT, Rodrigues JN (2014) External cardiac compression during cardiopulmonary resuscitation of patients with left ventricular assist devices. Interact Cardiovasc Thorac Surg 19:286–289. https://doi.org/10.1093/ICVTS/IVU117
8. Shinar Z, Bellezzo J, Stahovich M et al (2014) Chest compressions may be safe in arresting patients with left ventricular assist devices (LVADs). Resuscitation 85:702–704. https://doi.org/10.1016/J.RESUSCITATION.2014.01.003
9. Akhtar W, Gamble B, Kiff K et al (2022) Mechanical life support algorithm developed by simulation for inpatient emergency management of recipients of implantable left ventricular assist devices. Resusc Plus. https://doi.org/10.1016/J.RESPLU.2022.100254
10. Yuzefpolskaya M, Uriel N, Flannery M et al (2016) Advanced cardiovascular life support algorithm for the management of the hospitalized unresponsive patient on continuous flow left ventricular assist device support outside the intensive care unit. Eur Heart J Acute Cardiovasc Care 5:522–526. https://doi.org/10.1177/2048872615574107
11. Garg S, Ayers CR, Fitzsimmons C et al (2014) In-hospital cardiopulmonary arrests in patients with left ventricular assist devices. J Card Fail 20:899–904. https://doi.org/10.1016/J.CARDFAIL.2014.10.007
12. Haglund NA, Schlendorf K, Keebler M et al (2014) Is a palpable pulse always restored during cardiopulmonary resuscitation in a patient with a left ventricular assist device? Am J Med Sci 347:322–327. https://doi.org/10.1097/MAJ.0000000000000219
13. Cook JL, Colvin M, Francis GS et al (2017) Recommendations for the use of mechanical circulatory support: ambulatory and community patient care: a scientific statement from the American Heart Association. Circulation 135:e1145–e1158. https://doi.org/10.1161/CIR.0000000000000507
14. Saeed D, Feldman D, El BA et al (2023) The 2023 International Society for Heart and Lung Transplantation guidelines for mechanical circulatory support: a 10-year update. J Heart Lung Transplant 42:e1–e222. https://doi.org/10.1016/j.healun.2022.12.004
15. Resuscitation Council UK (2021) 2021 Resuscitation guidelines | Resuscitation Council UK. https://www.resus.org.uk/library/2021-resuscitation-guidelines. Accessed 10 Dec 2023
16. Bowles CT, Hards R, Wrightson N et al (2017) Algorithms to guide ambulance clinicians in the management of emergencies in patients with implanted rotary left ventricular assist devices. Emerg Med J 34:842–850. https://doi.org/10.1136/EMERMED-2016-206172
17. European Society of Cardiology (2017) Governing policies and procedures for the writing of ESC clinical practice guidelines
18. Medtronic Quick Reference Guide for HVAD controller alarms. https://www.medtronic.com/content/dam/medtronic-com/uk-en/patients/documents/hvad-patients/hvad-alarm.pdf. Accessed 20 Jan 2024
19. Abbott Heartmate 3 Left Ventricular Assist Device Patient Guide. https://www.cardiovascular.abbott/content/dam/bss/divisionalsites/cv/pdf/guides/hf-hm3-guide-to-understanding-lvad.pdf. Accessed 20 Jan 2024
20. Ogami T, Naka Y, Sanchez J et al (2020) Incidence and cause of persistent low flow alarm after HeartMate 3 left ventricular assist device insertion. J Heart Lung Transplant 39:S404. https://doi.org/10.1016/j.healun.2020.01.152
21. Saeed O, Jermyn R, Kargoli F et al (2015) Blood pressure and adverse events during continuous flow left ventricular assist device support. Circ Heart Fail 8:551–556. https://doi.org/10.1161/CIRCHEARTFAILURE.114.002000
22. Ahsan I, Faraz A, Mehmood A et al (2019) Clinical approach to manage gastrointestinal bleeding with a left ventricular assist device (LVAD). Cureus. https://doi.org/10.7759/CUREUS.6341
23. Nakahara S, Chien C, Gelow J et al (2013) Ventricular arrhythmias after left ventricular assist device. Circ Arrhythm Electrophysiol 6:648–654. https://doi.org/10.1161/CIRCEP.113.000113
24. Lizotte D (2021) Cardiac advanced resuscitation education. CSU ALS
25. Council Resuscitation (2021) Advanced Life Support algorithm
26. Yannopoulos D, Bartos J, Raveendran G et al (2020) Advanced reperfusion strategies for patients with out-of-hospital cardiac arrest and refractory ventricular fibrillation (ARREST): a phase 2, single centre, open-label, randomised controlled trial. Lancet 396:1807–1816. https://doi.org/10.1016/S0140-6736(20)32338-2
27. Belohlavek J, Kucera K, Jarkovsky J et al (2012) Hyperinvasive approach to out-of-hospital cardiac arrest using mechanical chest compression device, prehospital intraarrest cooling, extracorporeal life support and early invasive assessment compared to standard of care. A randomized parallel groups comparative study proposal. "Prague OHCA study." J Transl Med. https://doi.org/10.1186/1479-5876-10-163
28. Miyashita S, Ortoleva J, Vest A et al (2023) (813) Prolonged cardiopulmonary resuscitation with Lucas device in a patient with left ventricular assist device. J Heart Lung Transplant 42:S356. https://doi.org/10.1016/J.HEALUN.2023.02.826
29. Azeli Y, Barbería E, Fernández A et al (2022) Chest wall mechanics during mechanical chest compression and its relationship to CPR-related injuries and survival. Resusc Plus 10:100242. https://doi.org/10.1016/J.RESPLU.2022.100242