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Monitoring MCS patients on the intensive care unit: integrating haemodynamic assessment, laboratory data, and imaging techniques for timely detection of deterioration and recovery

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Monitoring of the patient supported with a temporary mechanical circulatory support (tMCS) is crucial in achieving the best possible outcome. Monitoring is a continuous and labour-intensive process, as cardiogenic shock (CS) patients can rapidly deteriorate and may require new interventions within a short time period. Echocardiography and invasive haemodynamic monitoring form the cornerstone of successful tMCS support. During monitoring, it is particularly important to ensure that adequate end-organ perfusion is achieved and maintained. Here, we provide a comprehensive overview of best practices for monitoring the CS patient supported by a micro-axial flow pump, veno-arterial extracorporeal membrane oxygenation, and both devices simultaneously (ECMELLA approach). It is a complex process that encompasses device control, haemodynamic control and stabilization, monitoring of interventions, and assessment of end-organ function. The combined, continuous, and preferably protocol-based approach of echocardiography, evaluation of biomarkers, end-organ assessment, and haemodynamic parameters is crucial in assessing this critically ill CS patient population.

Introduction

Monitoring plays a crucial role in the management of critically ill patients supported by percutaneous ventricular assist devices (pVADs) temporary mechanical circulatory support (tMCS) in the intensive care unit (ICU). Effective monitoring should be able to assess preload, detect signs of recovery or inadequate support needing escalation, detect signs of bi-ventricular failure and/or other complications, and identify any potential need for left ventricular (LV) venting (Class II, level of

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Table 1 Overview of various monitoring tools/metrics by system to assess critically ill cardiogenic shock patients during temporary mechanical circulatory support support

System	Monitoring tools
Neurological system	• NIRS monitoring • Daily sedation hold • (biomarkers: NSE)
Cardiovascular system	• Arterial wave form (e.g. pulse pressure, pulsus paradoxus, pulsus alternans, dicrotic notch, and ventriculo-arterial uncoupling) • Mixed venous saturation; pCO_2-gap; lactate levels and lactate clearance • Pulmonary artery catheter [PCWP, PAPi, CO/CI, SVR(i), CVP, and CPO(i)] • End-organ function evaluation (e.g. urine-output, troponin levels, liver tests, and kidney function) • Echocardiography (e.g. RV and LV output assessment, valve assessment, device, or cannula position) • Dynamic tests (fluid challenge, external pacing rate, PEEP-test, and PLR)
Pulmonary system	• PaO_2 and $paCO_2$ levels (right radial artery); PaO_2/FiO_2 ratio • ventilatory settings and trends in ventilation data • chest imaging (X-ray, CT, and lung ultrasound)
Haematological system	• Repetitive (anti)coagulation tests • Haemolysis tests (plasma free Hb) • Device related consumption coagulopathy (e.g. D-dimers, fibrinogen, and platelet count)
Specific device-related monitoring	• Purge pressures, CPO, SmartAssist—including motor current waveform—and device position (mAFP) • TMP, access/return pressures, RPM-trend, sweep flow, etc. (V-A ECMO)

CI, cardiac index; CO, cardiac output; CPO(i), cardiac power output index; CPO, cardiac power output; CT, computed tomography; CVP, central venous pressure; FiO_2, fraction of inspired oxygen; Hb, haemoglobin; LV, left ventricular; mAFP, micro-axial flow pump; NIRS, near-infrared spectroscopy; NSE, neuron-specific enolase; $paCO_2$, partial pressure of carbon dioxide in arterial blood; PaO_2, partial pressure of oxygen in arterial blood; PAPi, pulmonary artery pulsatility index; pCO_2, partial pressure of carbon dioxide; PCWP, pulmonary capillary wedge pressure; PEEP, positive end-expiratory pressure; PLR, platelet-to-lymphocyte ratio; RPM, rounds per minute; RV, right ventricular; SVR(i), systemic vascular resistance index; TMP, trans-membrane pressure; V-A ECMO, veno-arterial extracorporeal membrane oxygenation.

evidence C).[1] Beyond strict monitoring of the device's technical aspects, assessing patient–device interplay is pivotal at the beginning of tMCS to optimize pump flow and is crucial in later stages to foresee adverse events, capture signs of myocardial recovery, and determine the most appropriate timing for tMCS weaning or escalation.[2]

A comprehensive multi-modal monitoring approach encompassing both continuous and non-continuous techniques should be available at all times. Immediate bedside echocardiography is required to assess aetiology of shock and pVAD-specific issues, including device positioning. Additionally, echocardiography is indispensable during ICU management for the assessment of native heart function, identification of complications, and optimization of device settings. A complete list of monitoring tools and metrics is provided in *Table 1*.

We advise invasive haemodynamic monitoring in pVAD patients, where pulmonary artery catheterization (PAC) can provide information on native cardiac function, right ventricular (RV) involvement, and mixed venous oxygen saturation (SvO_2) and determine pulmonary artery pressures and vascular resistance.[3,4] The PAC also allows clinicians to monitor haemodynamic trends or responses to therapeutic interventions (e.g. increased pump flow, addition of inotropes, vasodilators, and combined tMCS) and assess recovery of native heart function. Moreover, though there is currently no robust scientific evidence, some haemodynamic parameters are provided directly from the micro-axial flow pump (mAFP) and controller, which are often based on derived values rather than direct measurements. Monitoring should also include repetitive end-organ function evaluation, through a standardized laboratory exams panel.[5–7] Monitoring should always include serial assessment of lactate from blood gas analyses, particularly in the early phase to ensure lactate clearance, combined with venous blood gas evaluation.[8] Serial coagulation checks are also required to prevent complications.[9] In the following chapters, we will dive into more detail on specific monitoring approaches for currently conventional tMCS devices.

Monitoring patients supported with a left-sided micro-axial flow pump

Echocardiography (trans-thoracic or trans-oesophageal in case of poor windows) used to assess pump position is the cornerstone for monitoring and follow-up of critically ill cardiogenic shock (CS) patients supported by a mAFP.[10] It is crucial to examine the cardiac anatomy immediately before pump implantation, to avoid future interactions of the pump with the mitral valve apparatus or other structures (a narrow angle of <126.5° between the aortic and mitral annulus in the apical three-chamber view predicts suction problems, haemolysis, and complications and is deemed a relative contraindication for mAFP insertion; *Figure 1*).[11] At minimum, daily echo assessment is mandatory for evaluation of pump position in the LV (distance between the aortic valve and pump inlet should be 3.5 cm in a CP/5.0 pump and 5 cm in a 5.5 pump[10]), native heart stroke volume [using the native LV outflow tract velocity time integral (LVOT VTI) that is also used in the process of weaning], valve

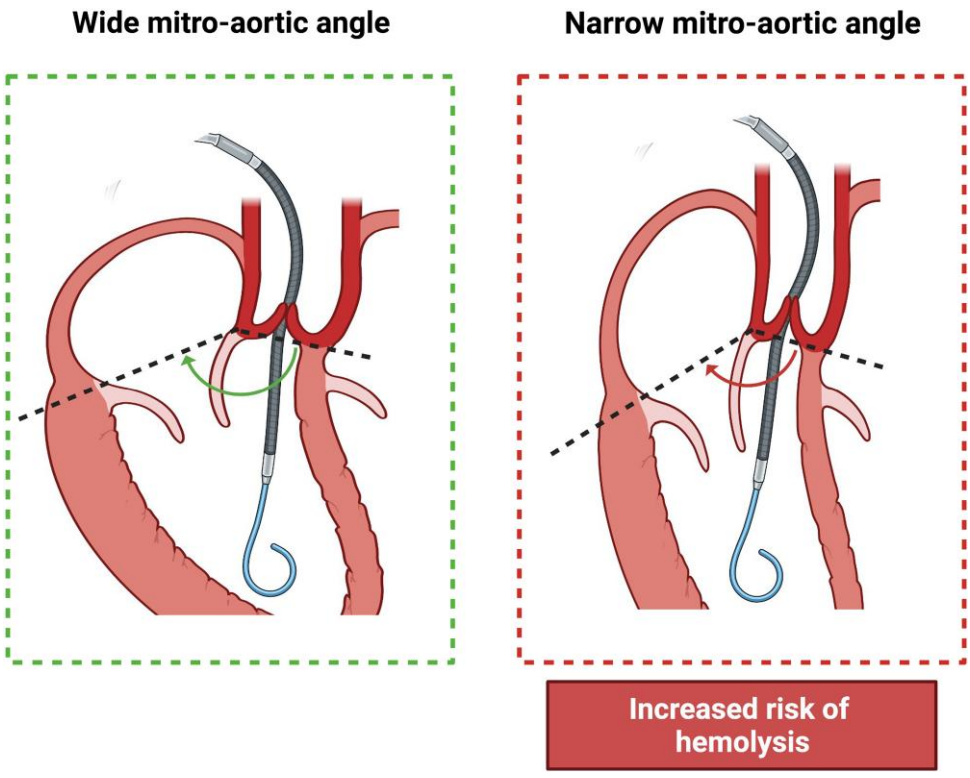

Figure 1 Importance of the correct micro-axial flow pump pump angle. The angle between the micro-axial flow pump/left ventricular outflow tract and the horizontal plane of the mitral valve is crucial to reduce risk of adverse events. The risk of suction events due to interaction with the mitral valve apparatus and the resulting potential for haemolysis is significantly reduced by maintaining a wide angle (>126.5°; left panel), whereas a more narrow angle (right panel) increases the risk of these events.

functions, and the function of the right ventricle (RV) to provide sufficient preload to the left mAFP.[12] Indeed, left-sided mAFPs are highly preload-dependent, and continuous follow-up of RV function is mandatory to prevent suction events, which can cause haemolysis and/or insufficient preload. In this regard, the use of PAC offers crucial information and is therefore recommended for use in any adjournment of CS. Moreover, PAC provides continuous and complete evaluation of the right [pulmonary artery pulsatility index (PAPi), RV output, and central venous pressure (CVP)] and, to a lesser extent, left circulation [cardiac output (CO), pulmonary capillary wedge pressure (PCWP), SvO_2, and venous CO_2 – arterial CO_2 (= pCO_2 – gap)]. In CS patients, the conditions can change rapidly and results of monitoring by PAC can therefore directly guide treatment.

Several recent observational studies have shown that routinely analysing a complete assessment is possibly associated with improved outcome in CS patients.[3,13,14] Additionally, easy dynamic bedside tests should not be forgotten in assessing fluid states in this high-risk patient group. For example, a passive leg raise test (in a well-sedated patient) can be of valuable information towards (relative) low filling state, next to a diagnostic fluid challenge. An incremental or decremental positive end-expiratory pressure (PEEP) challenge in mechanically ventilated patients can be very helpful in assessing the patient's filling state or the effect of PEEP on RV function. Haemolysis should be avoided at all times due to its prothrombotic effects, devastating effects on kidney function, and acute negative effects on the haemodynamic state of critically ill patients.[10] Therefore, it should be carefully monitored (especially on the first day after implementation) via plasma-free haemoglobin levels, lactate dehydrogenase (LDH), and/or bilirubin.[9]

The mAFP device console with placement signal and SmartAssist function provides the unique capability to reveal the position of the device and any underlying under-filling state or RV failure early on. If the LV waveform shows negative diastolic pressures with normal systolic pressures (intermittent suction), the filling and the volume status should be checked. On the other hand, if the LV shows both negative diastolic and systolic pressures (continuous suction), a positioning problem is more likely.[10] Cannulated limb has to be monitored closely, as antegrade perfusion is not used. Therefore, skin colour, arterial Doppler, and near-infrared spectroscopy (NIRS) may be used to detect eventual limb ischaemia (*Figure 2*).

Oxygenation monitoring

Monitoring patients on veno-arterial extracorporeal membrane oxygenation (V-A ECMO) should be focused on confirming adequate end-organ perfusion, optimal function of the device, identification of complications, and signs of myocardial recovery (*Figure 3*). This follows the same general principles discussed previously, but the

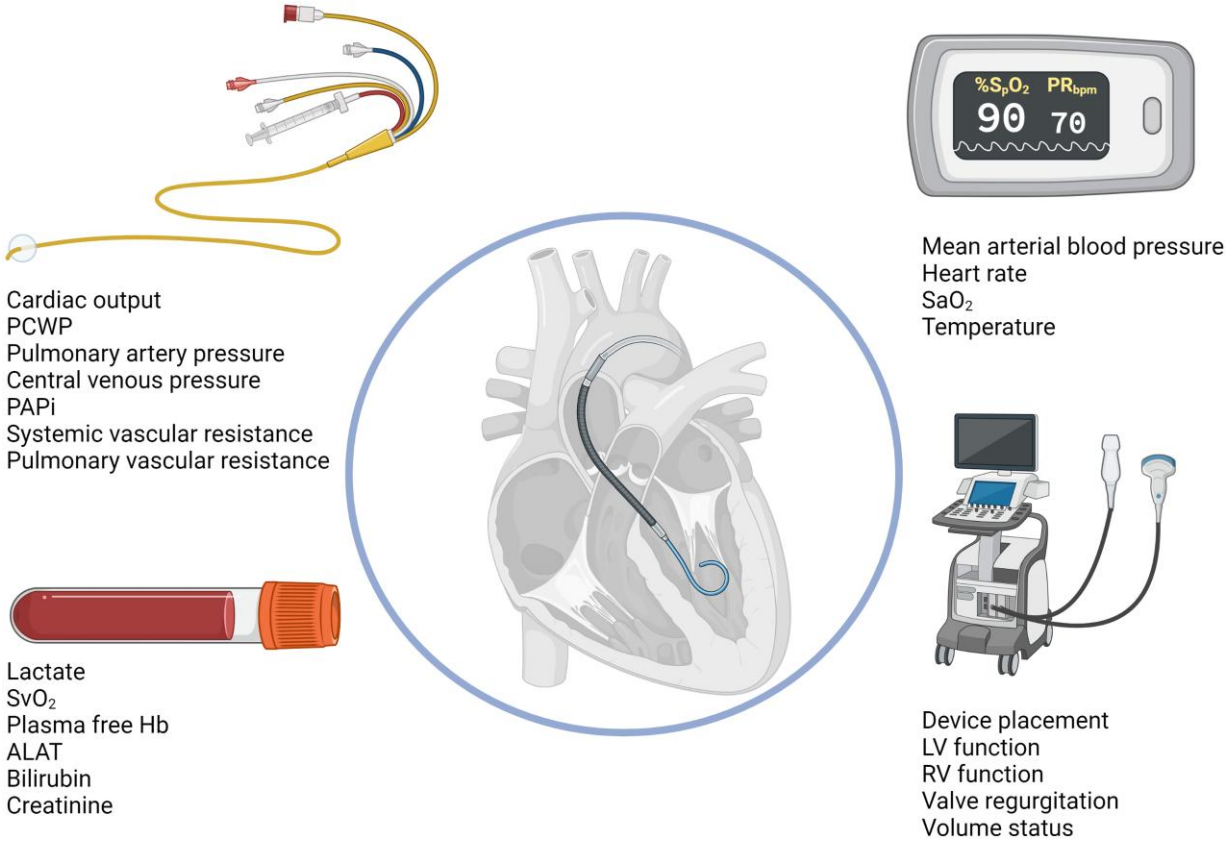

Figure 2 Monitoring tools for micro-axial flow pump. Overview of the tools used to monitor micro-axial flow pump support in critically ill cardiogenic shock patients. The combined, continuous, and preferably protocol-based approach of echocardiography, biomarkers and end-organ assessment, and haemodynamic parameters is crucial in assessing this critically ill patient population. ALAT, alanine transaminase; Hb, haemoglobin; LV, left ventricular; PaPi, pulmonary artery pulsatility index; PCWP, pulmonary capillary wedge pressure; RV, right ventricular; SpO_2, saturation of peripheral oxygen; SvO_2, venous oxygen saturation.

concept of extracorporeal life support (ECLS) with drainage of blood from the right atrium and retrograde aortic flow with femoral cannulation engenders several challenges in monitoring. Trans-pulmonary flow will be reduced and, in some instances, flow will be minimal, making thermodilution CO and SvO_2 from PAC unreliable. Peripheral oxygenation may be excellent despite severe pulmonary oedema, and oxygenation in the upper body may differ from the lower (differential hypoxaemia). Thus, specific protocols for monitoring these patients are required.

In case of severely reduced LV function, LV overload may be driven by pressure from the retrograde aorta flow and sustained trans-pulmonary flow.[15] Thus, preserved RV function may augment LV overload by promoting residual trans-pulmonary flow, as opposed to severe bi-ventricular failure where the risk of LV overload is lower.[16] Trend and changes in pulse pressure should be closely monitored on the arterial line; in general, a pulse pressure of >10–15 mmHg is desired. Pulmonary artery catheterization will enable assessment of PCWP and pulmonary pressure.[17] For echocardiography, attention should be paid to progressive LV dilatation, spontaneous echo contrast in the left atrium or LV, absent aortic valve opening, and thrombus in the LV cavity.[18] Either trans-thoracic echocardiography (TTE), or, if image quality is inadequate, trans-oesophageal echocardiography (TEE) should be performed daily at minimum.

With LV overload, the risk of pulmonary oedema and poor oxygenation of trans-pulmonary blood exists. As such, a condition can develop called differential hypoxaemia or Harlequin syndrome, where the lower body presents with good oxygenation from V-A ECMO and the upper body presents with poor oxygenation.[19] To detect this, the partial pressure of oxygen in the arterial blood (PaO_2) should always be monitored in the right upper extremity, as this is the first branching from the aorta after the coronary arteries. However, cases with watershed in the ascending aorta may miss this. Thus, PAC with monitoring of LV filling pressure is important, and chest X-ray and lung ultrasound may be of benefit in detecting pulmonary congestion.

Even with antegrade perfusion to the extremities from an arterial cannula, limb perfusion should be monitored using arterial Doppler, circumference follow-up, and temperature of the limb. Additionally, NIRS may be useful to detect signs of limb ischaemia.[20] With V-A ECMO, the erythrocyte shear stress generated by flow through the extracorporeal circuit or mAFP can induce erythrocyte lysis and release free haemoglobin; thus, haemolysis should be carefully monitored with measurement of plasma-free haemoglobin.

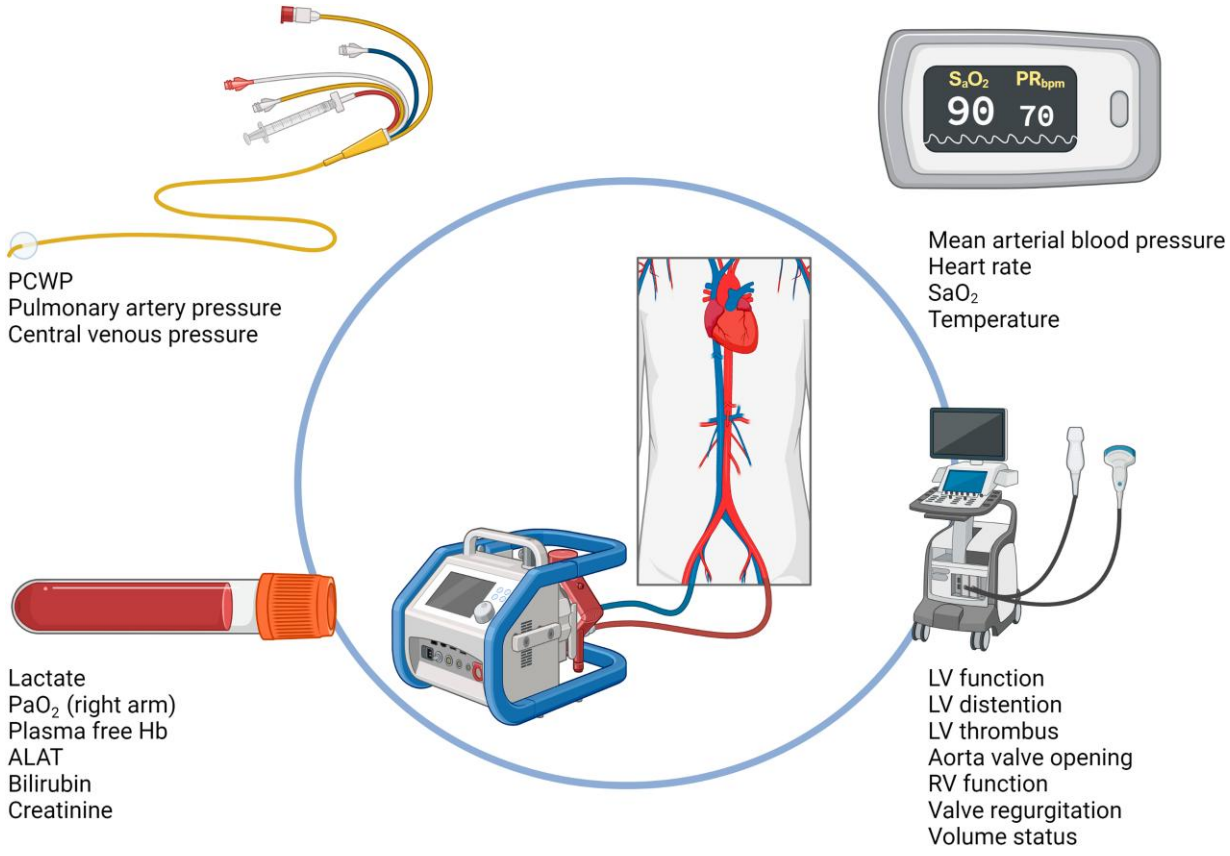

Figure 3 Monitoring tools for veno-arterial extracorporeal membrane oxygenation. Overview of the different monitoring tools during veno-arterial extracorporeal membrane oxygenation support in critically ill cardiogenic shock patients. Constant assessment of proper device function, end-organ perfusion and signs of recovery or deterioration, and potential complications are required. However, drainage of blood from the right atrium and retrograde aortic flow with femoral cannulation requires several additional steps in monitoring in the critically ill patient population. ALAT, alanine transaminase; Hb, haemoglobin; LV, left ventricular; PaO_2, partial pressure of oxygen in the arterial blood; PCWP, pulmonary capillary wedge pressure; RV, right ventricular; SaO_2, arterial blood oxygen saturation.

Monitoring should finally detect signs of myocardial recovery to plan weaning from ECLS or, in the absence of recovery, plan the transition to another tMCS, transplant or palliation. Trends of pulse pressure, arterial ejection period (the width of the arterial curve), changes in pulmonary pressures, and echocardiographic assessment of LVOT VTI are the among most utilized variables.[21] LVOT VTI allows beat-to-beat estimation of stroke volume and the immediate changes during alternations in V-A ECMO flow. Furthermore, LVOT VTI > 10–12 cm has been associated with better likelihood of successful weaning.[21]

Monitoring in patients supported with a combination of a micro-axial flow pump and peripheral veno-arterial extracorporeal membrane oxygenation

A multi-device strategy with a mAFP in addition to peripheral V-A ECMO (ECMELLA) increases the complexity of the tMCS therapy, with relevant implications for monitoring.[11,13-17] At each stage of ECMELLA support, continuous invasive haemodynamic monitoring of the patient and the parameters displayed by the two pumps should guide the clinical management. Additionally, bedside echocardiography is again paramount to assess residual LV-RV function, and laboratory parameters provide information on shock trend and end-organ function (*Figure 4*).

At the initiation of ECMELLA support, the primary goal is to balance the flow of the two devices and native heart function to provide a stable haemodynamic setting while optimizing device–patient interplay. The target haemodynamic effects of ECMELLA configuration at this stage include pulsatile systemic and pulmonary pressure waveforms, reduction in PCWP and CVP, stable flow from both devices with no alarms, and balanced support between the two devices determined with echocardiography (neutral position of inter-ventricular septum). Echocardiography is also essential to rule out some complications (e.g. cardiac tamponade or mAFP device displacement) and to assess the state of aortic and mitral valves. These are factors that can jeopardize ECMELLA outcome if not promptly addressed.[12] An adequate haemodynamic setting provided by ECMELLA will result in a reduced need for inotropes and more effective and rapid clearance of shock parameters, primarily lactate.[22] Clinical monitoring of the devices' cannulation sites and of the distal limbs, with respect to reperfusion needs, should be performed rigorously, as

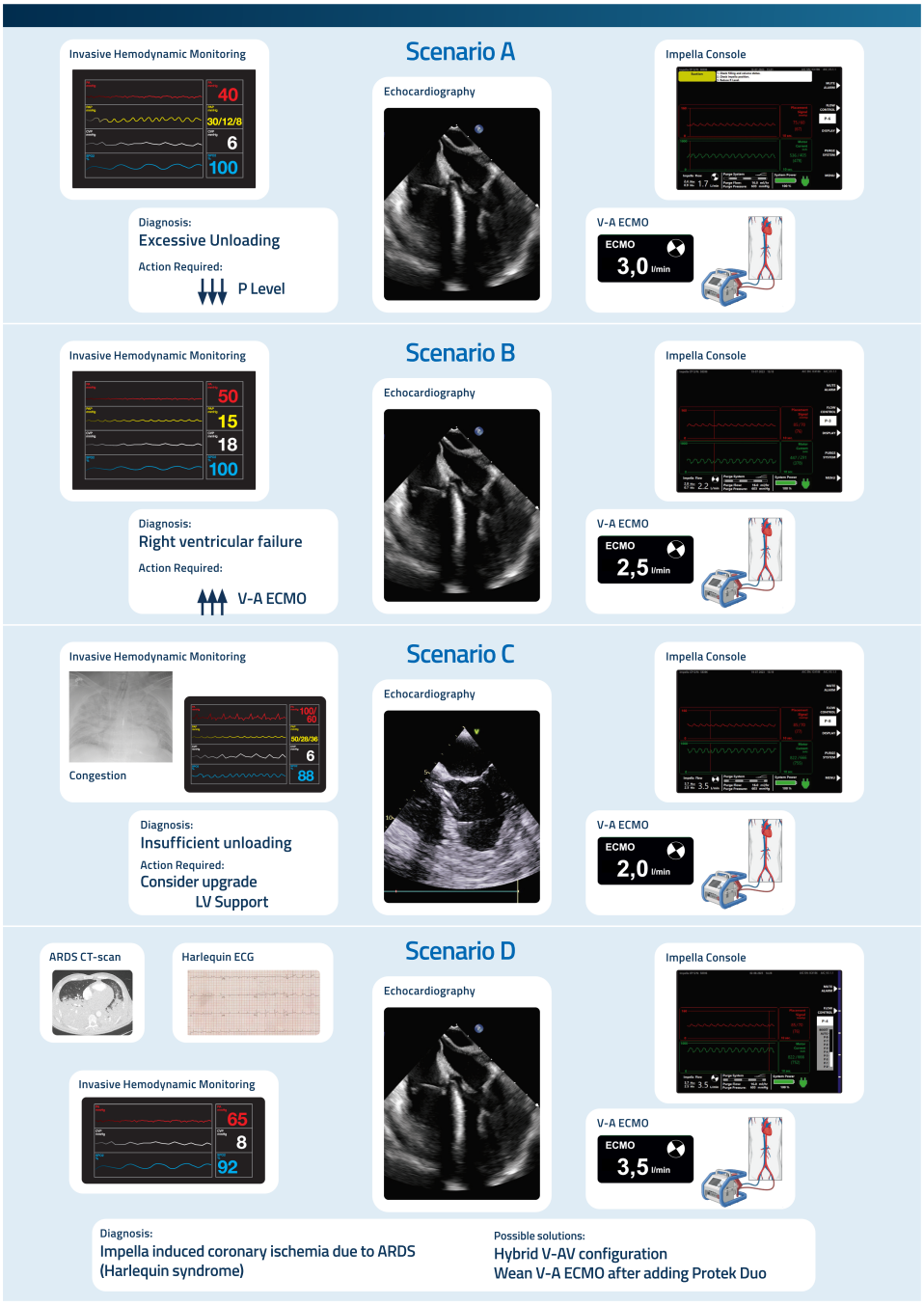

Figure 4 Monitoring tools for ECMELLA. The combined continuous assessment of invasive haemodynamic monitoring, bedside echocardiography, and readouts from the micro-axial flow pump or veno-arterial extracorporeal membrane oxygenation consoles are necessary for monitoring adverse changes in the patient's status. (Scenario A) Case of excessive unloading, as specified by the suction alarm and reduced flow indicated on the micro-axial flow pump console. This can be resolved by a fluid challenge or by reducing the P-level to lower the degree of left ventricular emptying and thus reducing the risk of haemolysis; it is important to validate whether the patient's organ perfusion is preserved on this lower P-level. (Scenario B) Presentation of right ventricular failure, as indicated by a severe drop in the pulmonary artery pressure coupled with a significant increase in the pulmonary vascular capacitance, a readout for the workload of the right ventricle. As a rescue, this patient can be initiated on veno-arterial extracorporeal membrane oxygenation to avoid impaired systemic perfusion. (Scenario C) Case presenting with need for left ventricular unloading. This is shown by insufficient left ventricular filling by echocardiography, as well as insufficient reduction of the pulmonary artery pressure X pulmonary artery pulsatility, indicating that native cardiac function has not been adequately supplanted. Notably, the SPO_2 is also significantly decreased, as insufficient unloading results in insufficient oxygenation despite veno-arterial extracorporeal membrane oxygenation. Additionally, the P-level of the micro-axial flow pump is P-8; in conclusion, these findings indicate that an upgrade to a higher level of left ventricular support should be considered. (Scenario D) A case showing micro-axial flow pump-induced coronary ischaemia on a background of acute respiratory distress syndrome. Due to the impaired pulmonary gas-exchange secondary to acute respiratory distress syndrome (ARDS), oxygen poor blood is ejected by the micro-axial flow pump in the proximal part of the ascending aorta, possibly moving the watershed area above the origin of the coronary arteries (differentially hypoxaemia or Harlequin syndrome) resulting in diffuse coronary ischaemia on the electrocardiogram (ECG). This can be resolved by switching to an ECMELLA hybrid configuration (veno-arteriovenous; V-AV) or by weaning veno-arterial extracorporeal membrane oxygenation after placement of a ProtekDuo cannula. LV, left ventricular; V-A ECMO, veno-arterial extracorporeal membrane oxygenation.

patients with profound CS have a high risk of peripheral ischaemia. The mixture of the retrograde flow of oxygenated blood provided by V-A ECMO and the anterograde flow of blood from pulmonary circulation provided by a mAFP drives the need for meticulous oxygenation monitoring to exclude Harlequin syndrome. The degree of oxygenation may greatly vary based on the presence and severity of pulmonary oedema, dictating the need for diligent mechanical ventilation regulation.

After ECMELLA support has reached stability, monitoring will help to assess organ reperfusion (laboratory exams and clinical parameters) and left and right heart congestion relief (echocardiography, chest X-ray, and haemodynamic parameters). Serial monitoring of coagulation parameters[9] with respect to the anticoagulation therapy, the coagulation derangements triggered by CS, and the presence of the two extracorporeal devices is crucial.

Data from complete monitoring systems also represent the turning point at the moment of weaning from ECMELLA and help to select a definitive therapeutic strategy and its timing. At this step, bedside echocardiography is crucial, especially to assess LV and RV function and to rule out valve injuries. Preferably, valve injuries should be addressed while still on support to ensure successful weaning. Limitations exist, as Doppler-based measurements may be affected by the mechanical noise of the device and continuous flow. In addition, common biplane LV ejection fraction measurement is not sufficient for detecting myocardial recovery or guiding weaning strategies.[23] Some evidence is also in favour of the prognostic role of haemodynamic parameters, including PAPi and PCWP, particularly with respect to poor outcomes.[24,25]

Pharmacological drug regulation, including inotrope titration and weaning, is also best performed by comprehensive monitoring of haemodynamic and echocardiographic parameters during support and especially when considering device weaning. Furthermore, axillary cannulation facilitates patients' rehabilitation, reduces complications, and is associated with favourable outcomes.[26–28] Thus, transition to axillary support should be considered early in patients predicted to be on prolonged tMCS support, based on haemodynamic and echocardiographic data.

Discussion

The armamentarium available to clinicians caring for tMCS-supported patients is broad, and new devices are constantly becoming available. Haemodynamic monitoring tools and echocardiography form the cornerstone of monitoring, supplemented with numerous biochemical tests to optimize the management of these patients.[29] In recent years, the PAC has experienced a true revival, especially in the domain of CS, and should likely be considered a standard monitoring tool in the management of tMCS-supported CS patients.[13,30]

It is important to note that few parameters of these tools have been validated for use/monitoring in critically ill patients supported by tMCS. Often, cut-off values and reasoning from classical (stable) cardiology and heart failure are applied to CS patients, but data regarding these values are often lacking. Therefore, these values should always be critically evaluated and considered, and it is better to rely on general trends rather than absolute values of the measured parameters.[9,12,29,31]

Finally, it is of paramount importance to establish a CS team for monitoring and treatment of tMCS-supported patients where different skills are present to guarantee a uniform and protocol-based approach 24/7. This could be ensured with different levels of expertise for all critical steps of tMCS management (anticoagulation management, weaning, device position assessment, etc.).[32] Implementing a widely accepted ICU protocol for each of these critical steps might be the key to reduce morbidity and mortality and improve outcomes in this critically ill patient population.

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Data availability

No new data were generated or analysed in support of this research.

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