Mechanical circulatory support. An expert opinion of the Association of Intensive Cardiac Care and the Association of Cardiovascular Interventions of the Polish Cardiac Society

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Kardiol Pol. 2021; 79 (12): 1399–1410;
DOI: 10.33963/KP.a2021.0169

Received:
October 24, 2021

Revision accepted:
December 2, 2021

Published online:
December 3, 2021

ABSTRACT

Mechanical circulatory support (MCS) methods are used in patients with both acute and chronic heart failure, who have exhausted other options for pharmacological or surgical treatments. The purpose of their use is to support, partially or completely, the failed ventricles and ensure adequate organ perfusion, which allows patients to restore full cardiovascular capacity, prolonging their life and effectively improving its quality. The three most popular devices include an intra-aortic balloon pump (IABP), percutaneous assist devices (including Impella, TandemHeart), and venoarterial extracorporeal membrane oxygenation (VA-ECMO). A multidisciplinary approach with the special participation of the Heart Team is required to determine the proper MCS strategy, the choice of the supporting method, and the time of its use. The studies published so far do not allow us to determine which MCS method is the safest and the most effective. Thus, the site experience and accessibility of the method seem to matter most today. MCS finds particular application in patients with acute coronary syndromes complicated by refractory cardiogenic shock, as well as in patients with acute heart failure of the high potential for reversibility. It can also serve as a backup for percutaneous coronary interventions of high risk (complex and high-risk indicated percutaneous coronary intervention [PCI], complex and high-risk indicated PCI [CHIP]). The use of appropriate supportive drugs, precise hemodynamic and echocardiographic monitoring, as well as optimal non-invasive or mechanical ventilation, are extremely important in the management of a patient with MCS. The most serious complications of MCS include bleeding, thromboembolic events, as well as infections, and hemolysis.

Key words: mechanical circulatory support-type and extension, indications and complications, multidisciplinary approach, hemodynamic and echocardiographic monitoring, ventilation and pharmacotherapy

Kardiol Pol 2021; 79, 12: 1399–1410

INTRODUCTION

For the past 20 years, there has been an ongoing search for novel medical therapies aimed at reducing mortality in patients with cardiogenic shock (CS) and acute cardiopulmonary failure. However, as the mortality rate in this population continues to be high, reaching 40% to 50%, the next step is to develop other therapeutic methods, such as mechanical circulatory support (MCS). Unfortunately, the choice of an MCS strategy is currently not supported by a sufficient number of studies providing unequivocal data. Precise recommendations for the use of MCS are also lacking.

The multivariable risk-benefit profiling to select patients for MCS requires a multidisciplinary approach, with the involvement of a Heart Team including a general cardiologist, an invasive cardiologist, an intensivist, a cardiac surgeon, and other specialists if needed. Due to advanced technology, current MCS systems enable full recovery of circulatory function, thus improving longevity and the quality of life of patients. Guidelines developed by American and European societies support the use of MCS to achieve full or partial ventricular support and adequate end-organ perfusion in patients with acute and chronic heart failure (HF), in whom all other medical or surgical treatments have failed. The management strategy depends on disease etiology, comorbidities, social and family history, as well as the experience of the implanting center. The choice of the MCS method, including the duration (short-, mid-, or long-term), type, and the extent of support, depends primarily on the patient's clinical status at the time of decision-making and destination therapy. In some patients, MCS is used as a bridge to transplant or a bridge to candidacy (BTC), while in others — as a bridge to recovery (BTR). Moreover, MCS may serve as a destination therapy for patients with contraindications to orthotopic heart transplantation (OHT) and as a bridge-to-decision (BTD) therapy for patients with acute HF (AHF) complicated by sudden cardiac arrest, who have an uncertain prognosis.

In this expert opinion statement, we discuss current approaches to MCS, as well as the management of intensive cardiac-care patients who require this type of treatment.

INDICATIONS FOR MECHANICAL CIRCULATORY SUPPORT

Patients with acute coronary syndromes complicated by cardiogenic shock

The major indication for MCS in patients with acute coronary syndrome is refractory CS complicating acute myocardial infarction (MI). Numerous MCS devices are available, with the 3 most popular being an intra-aortic balloon pump (IABP), a percutaneous ventricular assist device (VAD), such as Impella or TandemHeart, and venoarterial extracorporeal membrane oxygenation (VA-ECMO). They can be applied either alone or in combination and may provide right ventricular, left ventricular (LV), or biventricular support. According to the current European Society of Cardiology (ESC) guidelines, in patients with CS refractory to inotropic/vasopressor drugs, the early use of short-term MCS should be considered as a BTR or as a BTD on long-term VAD, OHT, or therapy withdrawal [1, 2]. IABP

may be considered in patients with CS, including treatment of the mechanical complication of acute MI or as a BTD on long-term MCS or OHT. However, IABP is not routinely recommended in post-MI CS.

To date, observational and randomized studies on MCS did not reveal any notable benefits in terms of improved survival in patients with CS complicating acute MI. Therefore, while awaiting further evidence, it seems that the most appropriate approach to the selection and use of the MCS device is for each center to develop a detailed protocol for the management of patients with CS complicating acute MI. The optimal timing for the initiation of MCS seems to be "classic" CS (stage C according to the Society for Cardiovascular Angiography and Interventions classification), with lactate levels higher than 2 mmol/l and before the onset of severe multiple organ injury. The selection between a percutaneous VAD and VA-ECMO should be guided primarily by the experience of the implanting center, both in terms of device implantation skills and patient management at the intensive cardiac care unit, and secondarily, by equipment availability.

Patients with acute heart failure

According to the recent 2021 European Society of Cardiology (ESC) guidelines, in patients with AHF, short-term MCS may be necessary to increase cardiac output and improve organ perfusion. Short-term MCS can be considered as a BTR or BTD [2]. Recent studies have shown that using a "standardized team-based approach" and predefined algorithms for early MCS implantation, supported by close monitoring (invasive hemodynamics, lactate levels, markers of end-stage organ damage), may potentially improve survival [3].

Mechanical circulatory support should be first considered in patients with AHF or CS with a high potential for recovery (e.g., in the course of myocarditis, peripartum cardiomyopathy, or Takotsubo syndrome) [2]. However, selecting an appropriate device remains a challenge owing to the lack of data from large randomized controlled trials. Although the guidelines do not recommend routine use of an IABP in patients with CS [2], it may still be considered in patients with hemodynamic instability, especially that of non-ischemic etiology and refractory to drug therapy, as a BTD or BTR. Other short-term MCS devices were compared with IABP in small randomized trials with inconclusive results [4]. Impella and TandemHeart were shown to offer greater hemodynamic benefits vs IABP in patients with CS, although without effect on survival [5]. Therefore, IABP remains the most common MCS device. High-quality evidence on the use of Impella in patients with CS without acute MI is lacking.

It was shown that VA-ECMO offers a high degree of biventricular support in a wide range of clinical scenarios. Therefore, it is increasingly used as the first-line strategy in patients requiring MCS [6,7]. Aso et al. [8] reported significant benefits of VA-ECMO use in combination with IABP vs VA-ECMO alone in patients with CS, including improved survival and a higher proportion of patients weaned from VA-ECMO. The use of Impella in patients on VA-ECMO support (ECMELLA) was also reported to improve treatment outcomes [9]. The use of MCS (ECMO, Impella RP) may be also considered in isolated acute right HF [10,11].

SHORT-TERM MECHANICAL CIRCULATORY SUPPORT IN INTERVENTIONAL CARDIOLOGY

In interventional cardiology, indications for percutaneous left VAD (LVAD) implantation may be both urgent and elective. Urgent indications are directly related to the patient's clinical status and were described above. This refers primarily to patients with CS or acute ischemic HF who require concomitant coronary procedures.

The need for elective LVAD implantation results from the changing profile of patients undergoing percutaneous coronary interventions (PCIs). There is currently no universal definition of complex and high-risk indicated PCI (CHIP). Nevertheless, in recent years, a range of factors associated with higher procedural risk have been identified (Table 1) [10, 12]. In severe peripheral vascular disease, alternative access, such as a subclavian or axillary artery, may be considered. The use of axial-flow pumps is contraindicated in severe aortic stenosis or moderate/severe aortic regurgitation. Patient eligibility for percutaneous LVAD implantation during CHIP should be determined by a Heart Team. The decision-making should be guided by cardiac output, the presence of comorbidities, the duration of support, the risk of bleeding, as well as ischemic events associated with the planned coronary intervention and the type of MCS device used, including the risk of local complications.

Local complications (bleeding, hematomas, limb ischemia) constitute an important limitation to the use of percutaneous LVAD. Therefore, it is necessary to puncture properly and to secure hemostasis after the procedure. Notably, the risk of complications increases with a longer duration of LV support. Therefore, in the case of elective CHIP procedures, an optimal approach is to remove the device on completion of the procedure. A comparison of available percutaneous ventricular assist devices, their characteristics, and hemodynamic effects is presented in Table 2.

SHORT- AND LONG-TERM MECHANICAL CIRCULATORY SUPPORT

Orthotopic heart transplantation remains the treatment of choice for patients with end-stage HF, mainly because of very good long-term outcomes. Thanks to advanced technology, the implantation of MCS devices (particularly centrifugal continuous-flow LVADs) was shown to yield similar 5-year outcomes as OHT. Considering a limited number of donors, the differences between the bridge to transplant and destination therapy strategies are becoming increasingly less distinct, and this tendency will be even more pronounced in the future. The use of MCS as a BTT therapy is summarized in Table 3.

Table 1. Factors associated with complex and high-risk indicated percutaneous coronary intervention (CHIP)

1. Clinical characteristics of high-risk patients	2. Anatomical and morphological characteristics of high-risk lesions
• advanced age (>75years) • diabetes • heart failure with LVEF ≤35% • acute coronary syndrome • previous cardiac surgery • peripheral vascular disease • severe chronic kidney disease (GFR <30 ml/min/1.73 m^2) • chronic obstructive pulmonary disease • concomitant severe aortic valve disease or severe mitral regurgitation	• unprotected left main coronary artery disease • degenerated vein grafts • severely calcified lesions requiring rotational atherectomy • a single remaining patent vessel • chronic total occlusion, especially in patients with multivessel disease
3. Hemodynamic status of the patient	

Abbreviations: GFR, glomerular filtration rate; LVEF, left ventricular ejection fraction

Table 2. Technical and clinical characteristics of common percutaneous mechanical circulatory support devices

Characteristics	IABP	VA-ECMO	Impella (2.5, CP, 5.0, 5.5)	iVAC 2L	TandemHeart
Inflow/outflow	Aorta	Right atrium — aorta	Left ventricle — aorta	Left ventricle — aorta	Left ventricle — aorta
Mechanism of action Pneumatic		Centrifugal flow	Axial flow	Pulsatile flow	Centrifugal flow
Site and type of access	Femoral artery/ /percutaneous	Femoral artery and vein/percutaneous	Femoral artery/ /percutaneous	Femoral artery/ /percutaneous	Femoral artery and vein/ /percutaneous
Sheath size (Fr)	7–8	Venous: 17–21 Arterial: 16–19	14–21	17	Venous: 21 Arterial: 12–19
Maximum flow (l/min)	0.3–0.5	7.0	3.7–5.5	2.8	4.0
Duration of support	2–5 days	7–10 days	6 h – 10 days	6 h – 10 days	Up to 14 days
LV function-dependent	+	–	–	–	–
Synchrony with cardiac function	+	–	–	–	–
Left ventricular unloading	+	–	+++	+	+++
Afterload	↓	↑↑	↓	↓	↑
MAP	↑	↑↑	↑↑	↑↑	↑↑
Cardiac index	↑	↑↑↑	↑↑↑	↑↑	↑↑↑
PCWP	↓	↔	↓↓	↓	↓↓
LVEDP	↓	↔	↓↓	↓↓	↓↓↓
Coronary artery perfusion	↑	↔	↑	↑	↔
Myocardial oxygen consumption	↓	↔	↓↓	↓↓	↓←
Difficulties in device implantation and patient management	+	+++	++	++	+++
Possible complications	Lower limb ischemia, bleeding	Lower limb ischemia, bleeding, hemolysis	Hemolysis, lower limb ischemia, bleeding	Hemolysis, lower limb ischemia, bleeding	Hemolysis, lower limb ischemia, bleeding
Contraindications	Moderate to severe aortic regurgitation, critical femoral/iliac artery stenosis	Moderate to severe aortic regurgitation, severe iliac/femoral artery stenosis, contraindications to anticoagulation	Severe aortic valve disease, mechanical aortic valve, left ventricular thrombus, severe iliac/femoral artery stenosis, contraindications to anticoagulation	Severe aortic valve disease, mechanical aortic valve, left ventricular thrombus, severe iliac/ femoral artery stenosis, contraindications to anticoagulation	Moderate to severe aortic regurgitation, left atrial thrombus, severe iliac/femoral artery stenosis, contraindications to anticoagulation

Abbreviations: IABP, intra-aortic balloon pump; VA-ECMO, venoarterial extracorporeal membrane oxygenation; LV, left ventricular; MAP, mean arterial pressure; PCWP, pulmonary capillary wedge pressure; LVEDP, left ventricular end-diastolic pressure

Table 3. Mechanical circulatory support as a bridge to transplant

MCS as a bridge to transplant		
Indications for implantation	**When?**	**Estimated duration of mechanical support**
1. In patients referred for OHT, with an estimated prolonged waiting time for donor's heart (e.g., body mass >100 kg; blood group B), with frequent decompensation episodes (INTERMACS 4) or hospitalizations requiring inotropic treatment (INTERMACS 3) 2. In patients with dilated or ischemic cardiomyopathy with left ventricular impairment (or distention) and normal or slightly impaired right ventricular systolic function 3. In patients without contraindications to long-term anticoagulant treatment with vitamin K antagonist and antiplatelet therapy with acetylsalicylic acid, with adequate support from the family or relatives, independent or only slightly limited in daily functioning	1. In patients referred for urgent OHT, MCS implantation should be considered after a waiting time span defined by the Heart Failure Heart Team and dependent on the patient's hemodynamic status, disease etiology, and technical feasibility of implantation. If the patient is hemodynamically stable and receives inotropic support or short- to mid-term MCS, the waiting time should not exceed 2 weeks 2. In patients referred for urgent OHT, with severe arrhythmia or increased catecholamine levels, an MCS device should be implanted within 48 to 72 hours 3. In patients referred for elective OHT, long-term MCS (preferably CF-LVAD) may be considered in candidates with low chances of receiving an organ (body mass >120 kg) 4. In patients classified as INTERMACS class 1 (cardiogenic shock), implantation of mid-term MCS devices is preferred, with a subsequent switch to long-term support (LVAD or TAH) in the absence of an organ donor within the time span defined by the team (usually within 10–30 days)	In this population, long-term LVAD support is preferred. This type of treatment is associated with 2- to 5-year survival, which is comparable to that for OHT

MCS as a bridge to transplant			
Indications for implantation	**When?**	**Estimated duration of mechanical support**	**What type of device should be used?**
If the condition that constitutes a contraindication to transplant is potentially reversible or curable. MCS therapy may increase the chances of curing a concomitant condition (eg, pulmonary hypertension, early-stage cancer, or a post-cancer treatment condition within a period of fewer than 5 years from intervention/treatment)	In hemodynamically stable patients classified as INTERMACS class 3–5. Usually as an elective procedure. The intervention should be preceded by specialist consultations, and subsequent treatment should be administered in cooperation with an implantation or transplantation center	Unknown, potentially long	Long-term CF-LVAD is preferred. If biventricular support is needed, TAH or biventricular VAD may be used

MCS as a bridge to decision			
Indications for implantation	**When?**	**Estimated duration of mechanical support**	**What type of device should be used?**
In cardiogenic shock (INTERMACS 1) or in the case of hemodynamic deterioration and/or multiple organ injury despite therapy escalation (INTERMACS 2)	Simultaneously with the decision to institute mechanical circulatory support, often during resuscitation	Unknown, potentially moderately long	Owing to the availability and quick implantation procedure, short-term MCS devices are preferred (mainly VA-ECMO). In potentially reversible cardiogenic shock, mid-term devices can be are preferred (eg, LEVITRONIX)

MCS as a bridge to recovery			
Indications for implantation	**When?**	**Estimated duration of mechanical support**	**What type of device should be used?**
In acute heart failure without permanent damage to the contractile apparatus and if recovery of normal function is possible (eg, myocarditis, poisoning, peripartum cardiomyopathy, postcardiotomy or post-OHT cardiogenic shock, rarely in dilated cardiomyopathy)	The decision should be made immediately after pharmacological options have failed	Unknown, potentially moderately long (months) or, less frequently, long (years)	Owing to the availability and quick implantation procedure, mid-term MCS devices are preferred - centrifugal-flow pumps such as LEVITRONIX or pneumatic pumps such as Religa or Berlin Heart (in pediatric patients). The use of CF-LVAD is contraindicated or implantation is technically not feasible because the pathology often involves both ventricles (poisoning, myocarditis)

MCS as destination therapy			
Indications for implantation	**When?**	**Estimated duration of mechanical support**	**What type of device should be used?**
Not eligible for OHT, most often due to age (>70 years) or with chronic comorbidities: chronic kidney disease, irreversible pulmonary hypertension, or with contraindications to immunosuppressive treatment (history of cancer) or pathological obesity	Preferred - if the patient presents with signs and symptoms of heart failure with at least 2 hospitalizations per year (INTERMACS 4–5) The procedure should be performed in hemodynamically stable patients and should be preceded by gastrointestinal imaging studies (gastroscopy, colonoscopy) to exclude contraindications to chronic anticoagulation	Long-term	CF-LVAD preferred. TAH is not approved for use in this indication

MSC, mechanical circulatory support; OHT, orthotopic heart transplantation; CF-LVAD, continuous-flow left ventricular assist device; TAH, total artificial heart; VA-ECMO, veno-arterial extracorporeal membrane oxygenation; VAD, ventricular assist device, LVAD, left ventricular assist device

EXTRACORPOREAL MEMBRANE OXYGENATION SUPPORT FROM THE PERSPECTIVE OF AN INTERVENTIONAL CARDIOLOGIST, AN INTENSIVIST, AND A CARDIAC SURGEON

Interventional cardiology

There is a general agreement that access to an effective MCS device is needed in at least 2 clinical scenarios in the setting of interventional cardiology: during a PCI in patients with MI complicated by CS and in patients undergoing CHIP. Since the publication of the IABP-SHOCK II study, which revealed significant limitations to IABP use, there has been an increasing interest in other MCS strategies, including VA-ECMO [13, 14].

Originally used in cardiac surgery, VA-ECMO has become an indispensable part of modern intensive care. In Poland, the vast majority of MCS equipment can be found at cardiac surgery and intensive care units, outside the catheterization laboratories. It is widely acknowledged that time is a key factor in interventional treatment for ST-segment elevation myocardial infarction and CS. Relocating and launching VA-ECMO in the catheterization laboratory necessitate an immediate decision and highly effective team cooperation based on simple and clear management algorithms. Unfortunately, the lack of such guidelines hinders the application of VA-ECMO. Moreover, the prolonged VA-ECMO use in patients with CS increases afterload, and, in some patients, the lack of LV decompression causes progressive distention with profound LV failure. In such cases, additional or supportive active-unloading therapy with a percutaneous axial-flow pump (ie, Impella) is mandatory. This might improve survival and reduce the long-term risk of HF caused by LV overload. However, such a combined MCS strategy for CS entails additional risk, with vascular complications in the first place. Retroperitoneal hemorrhage, arterial laceration from the use of large-bore femoral cannulas, and distal limb ischemia underlie the subsequent higher need for transfusion and the risk of acute kidney injury. Thus, meticulous use of the procedure with the help of a vascular surgeon and/or safety devices is highly recommended. All things considered, it must be emphasized that the complexity and cost-effectiveness of the combined approach are high and the number of studies reporting such benefits is limited [9, 15].

The decision on whether to use hemodynamic support in patients undergoing CHIP remains a challenge, with the widely available risk scores (EuroSCORE II, Syntax I, and II) being of limited supportive value for decision-making. On the one hand, the individual patient's characteristics should be assessed, including comorbidities, LV function, previous revascularization procedures, as well as the estimated duration and complexity of PCI. On the other hand, the feasibility of the procedure in extremely difficult cases (rotational atherectomy, treatment of chronic total occlusion, or distal left main artery stenosis) has to be accurately assessed. It is important to mention the problem of limb ischemia and the possibility of its prevention (both Impella and ECMO) by puncturing the antegrade artery below the site of large vascular access and connecting the sheath with the second arterial access, which ensures the inflow of blood to the limb. It is also important to secure the removal of the device by a vascular surgeon or using a hemostatic system.

The most important aspects to consider in MCS strategy selection depending on a clinical scenario are presented in Table 4.

Intensive care

The typical indications for VA-ECMO in the intensive care setting include refractory CS, massive pulmonary embolism, an overdose of cardiotoxic drugs, or severe hypothermia [16]. The use of VA-ECMO during cardiopulmonary resuscitation in hospitalized patients was reported to increase survival from 20% to 40% [17]. While the institution of ECMO itself does not cure a patient with organ failure, it provides more time to implement therapies aimed at reversing the underlying pathological process.

The key to effective VA-ECMO therapy is a high standard of intensive care achieved and maintained by continuous medical education together with the assessment of therapy outcomes and failures [18]. The intensivist working at an ECMO unit is responsible for blood flow optimization in the ECMO system and a daily echocardiographic assessment of LV emptying. The success of VA-ECMO therapy is also determined by such factors as the availability of a protocol for LV unloading using different strategies, expertise in invasive mechanical ventilation, and the ability to identify and reverse differential hypoxia [19]. The most common modes of LV unloading during VA-ECMO are IABP, percutaneous transaortic LVAD (Impella), atrial septostomy, and direct surgical LV venting. Finally, an important determinant of VA-ECMO success is knowledge of escalation strategies (LVAD, OHT), as well as conscious decision-making skills in terms of therapy de-escalation.

Cardiac surgery

In cardiac surgery, VA-ECMO devices are indicated for circulatory support in patients with postcardiotomy low cardiac output syndrome and refractory CS [20] (stage D ["deteriorating"] and E ["extremis"] according to the Society for Cardiovascular Angiography and Interventions Clinical Expert Consensus Statement on the Classification of Cardiogenic Shock). VA-ECMO is used directly during the procedure in patients with severe hemodynamic collapse, in patients who cannot be weaned from cardiopulmonary bypass after the procedure, or in those who develop low cardiac output syndrome immediately after the procedure. Moreover, VA-ECMO is typically used as a BTR strategy. In some cases, it may be used as a BTD that includes either LVAD implantation or OHT. The most common complication of postcardiotomy ECMO circulatory support is major

Table 4. Use of percutaneous ventricular assist devices in complex and high-risk indicated percutaneous coronary intervention (CHIP)

Device	IABP	AFP	VA-ECMO
Use of percutaneous VAD in CHIP			
Indications	In selected cases when the vascular access precludes AFP use (common femoral artery diameter >4 mm, without excessive tortuosity)	Indicated in cases with adequate vascular access (common femoral artery diameter >6 mm, without excessive tortuosity)	To be considered if biventricular support is required, with the need for oxygenation support
Evidence from clinical trials and studies	BCIS-1 study	PROTECT II and cohort studies	No data available
Use of percutaneous VAD in patients with HR-AMI without CS			
Indications	Not recommended	Impella CP implantation is possible and effective as the primary strategy for left ventricular unloading	Not recommended
Evidence from clinical trials and studies	IABP-SHOCK II	Preclinical studies; a single pilot study	No data available
Use of percutaneous VAD in patients with CS			
Indications	Routine use is not recommended; it may be considered in patients with mechanical complications of AMI and patients with CS unrelated to AMI.	Impella CP may be used for short-term support in patients with CS (stage C or D) with a potentially reversible cause or in candidates for VAD implantation or heart transplant	May be used as short-term support in patients with CS (stage C, D, or E), particularly in those with respiratory failure, with a potentially reversible cause, or in candidates for VAD implantation or heart transplant. To be considered in patients with refractory sudden cardiac arrest
Evidence from clinical trials and studies	IABP-SHOCK II	Small randomized trials and cohort studies	Prospective and retrospective cohort studies

IABP, intra-aortic balloon pump; AFP, axial-flow pumps; VA-ECMO, veno-arterial extracorporeal membrane oxygenation; VAD, ventricular assist device; HR-AMI, heart rupture after acute myocardial infarction; CS, cardiogenic shock; AMI, acute myocardial infarction

bleeding, with almost half of the patients requiring surgical intervention. Postcardiotomy ECMO support is associated with low survival rates (in-hospital mortality, 70%; 5-year survival, 15%).

Moreover, ECMO may be used as short-term MCS in patients classified as INTERMACS level 1 and 2, in the absence of contraindications and if long-term hemodynamic support or OHT is feasible [16]. Preoperatively, ECMO is used to achieve stability in patients with CS. By restoring the pump output, ECMO stabilizes organ function (mainly the kidneys and the liver), resolves potential bleeding disorders, and allows a comprehensive assessment of the patient's condition before deciding on subsequent management.

VA-ECMO can lead to the development of Harlequin syndrome, which is associated with a difference in oxygenation in the blood reaching the upper and lower half of the body. The upper body receives poorly oxygenated blood pumped by the heart, and the lower body receives well-oxygenated blood from ECMO. This depends on the ratio of cardiac output and influx from ECMO. The solution is to shift the returning cannula closer to the heart (e.g., into the right subclavian artery), central cannulation (through thoracotomy), or add another cannula to the venous system (the so-called veno-arterial-venous ECMO).

HEMODYNAMIC MONITORING OF PATIENTS ON MECHANICAL CIRCULATORY SUPPORT

Cardiac monitoring in critically ill cardiac patients (particularly those with CS complicating AHF) is fundamental not only for the diagnostic process but also for treatment optimization and outcome evaluation. However, studies conducted so far revealed no significant differences between invasive and minimally invasive or noninvasive hemodynamic monitoring in terms of improved outcomes [21, 22]. It seems that the decision on the type of hemodynamic monitoring in critically ill patients should be guided primarily by a detailed clinical assessment, as well as local equipment availability and training. Advanced monitoring incorporates both noninvasive and invasive continuous hemodynamic monitoring. Noninvasive techniques include clinical assessment: blood pressure, heart rate, diuresis, metabolic parameters, transthoracic and transesophageal echocardiography, impedance cardiography, and noninvasive arterial blood pressure waveform monitoring. Invasive monitoring from arterial and central venous catheters, as well as pulmonary artery catheters, provides the measurement of arterial pressure, intracardiac filling pressures, arterial and venous blood gases, and cardiac index (invasive arterial and venous blood pressure monitoring, venous pressure monitoring, right heart catheterization [thermodilution, continuous cardiac output, mixed venous oximetry], transpulmonary thermodilution [PICCO, LIDCO], Fick method). Additionally, in some cases, it is necessary to assess intra-abdominal pressure to evaluate organ perfusion pressures [23-26]. Notably, no single method of hemodynamic monitoring itself will improve the patient's prognosis: it must implicate proper therapeutic decisions. There are no optimal hemodynamic parameters that would apply to all patients and individual hemodynamic parameters should be combined and integrated depending on the patient's clinical status. Hemodynamic abnormalities depending on the type of MCS device are

Table 5. Hemodynamic abnormalities depending on the type of mechanical circulatory support device [27]

	IABP	Impella	TandemHeart	VA-ECMO
LV contractility	↔	↔	↔	↔
TPR	↔	↔	↔	↔
LV flow	↑	↓	↓	↓
Total CO	↑	↑↑	↑↑	↑↑↑
CVP	↔ or ↓	↔ or ↓	↔ or ↓	↓
PCWP	↔ or ↓	↓	↓	↑ or ↔[a]
MAP	↑	↑↑	↑↑	↑↑
Total CPO	↑	↑↑	↑↑	↑↑
PVA	↔ or ↓	↓↓	↔ or ↓	↑↑
MVO_2	↓	↓↓	↔ or ↓	↑↑

[a]ECMO use may lead to a decrease in LV preload, but also may provoke an increase of LV afterload with a subsequent undesirable increase in cardiac work and oxygen consumption

Abbreviations: CO, cardiac output; CPO, cardiac power output; CVP, central venous pressure; MVO_2, myocardial oxygen consumption; PVA, pressure-volume area; TPR, total peripheral resistance; other — see Table 2

Table 6. General characteristic and hemodynamic assessment depending on the monitoring method

Method	CO/CI	CVP/RAP	PAP	LAP	SVR	PVR	TFC	$SvO_2/SCvO_2$	Invasiveness	Availability
Pulmonary artery catheterization	+++	+++	+++	++	+++	+++	-	+++	+++	+++
Impedance cardiography	+/++	–	–	–	++	-	++	–	0	+
Doppler echocardiography	++	++	++	+	–	–	–	–	0/+	+++
Transpulmonary thermodilution	+++	+/–	–	–	–	–	+	+	++	+++
Invasive/noninvasive pressure waveform analysis	+/++	–	–	–	–	–	–	–	++/0	++

Abbreviations: CI, cardiac index; CVP, central venous pressure; LAP, left atrial pressure; PAP, pulmonary artery pressure; PVR, pulmonary vascular resistance; SVR, systemic vascular resistance; SvO_2, mixed venous oxygen saturation; $SCvO_2$, central venous oxygen saturation; RAP, right atrial pressure; TFC, total fluid capacity; other — see Figure 1

Table 7. Guideline recommendations for the use of invasive hemodynamic monitoring (see the text)

Class of recommendation 1C
Routine use of cardiac catheterization in patients with shock is not recommended. Routine assessment of cardiac output is not recommended if a satisfactory response to treatment is obtained. Cardiac output should be assessed in patients with hemodynamic instability despite treatment and/or to evaluate response to fluid replacement therapy and treatment with vasoactive drugs. Serial hemodynamic assessment in patients with shock is recommended
Class of recommendation 2B
Echocardiographic hemodynamic assessment as an alternative to invasive assessment should be considered to determine the type of shock.
Class of recommendation 2C
In complex cases, pulmonary artery catheterization or transpulmonary thermodilution should be considered to determine the type of shock. Pulmonary artery catheterization should be considered in patients with refractory CS and right ventricular failure. Pulmonary artery catheterization or transpulmonary thermodilution should be considered in patients with CS and ARDS.

Abbreviations: ARDS, acute respiratory distress syndrome; CS, cardiogenic shock

presented in Table 5 [27], while the hemodynamic parameters assessed using different hemodynamic monitoring methods are presented in Table 6**.**

In line with the recommendations of the European Intensive Care Society (Consensus on circulatory shock and hemodynamic monitoring Task Force of the European Society of Intensive Care Medicine) [28], cardiac hemodynamic parameters in patients with shock are assessed to identify the type of shock if the clinical presentation is unclear, decide on the type of therapy, and assess treatment response. It seems that in the absence of unequivocal data on the choice of optimal hemodynamic monitoring and predicting survival benefits, these goals are clinically justified. Guideline recommendations for the use of invasive hemodynamic monitoring are summarized in Table 7.

SUPPORTIVE MEDICAL THERAPY IN PATIENTS ON MECHANICAL CIRCULATORY SUPPORT

Intensive care patients receiving MCS therapy require adequate pharmacological support. Fluid therapy, inotropic/vasopressor therapy, as well as prevention of bleeding and thromboembolic events, are the mainstay of medical therapy in this setting. The myocardial and vascular effects

Table 8. Effect of inotropic drugs on selected hemodynamic parameters [29]

Medication/dose	Hemodynamics
Dopamine 0.5–2 μg · kg^{-1} · min^{-1}	↑CO
Dopamine 5–10 μg · kg^{-1} · min^{-1}	↑↑CO, ↑SVR
Dopamine 10–20 μg · kg^{-1} · min^{-1}	↑↑SVR, ↑CO
Norepinephrine 0.05–0.4 μg · kg^{-1} · min^{-1}	↑↑SVR, ↑CO
Epinephrine 0.01–0.5 μg · kg^{-1} · min^{-1}	↑↑CO, ↑↑SVR
Vasopressin 0.02–0.04 U/min	↑↑SVR, ↔PVR
Dobutamine 2.5–20 μg · kg^{-1} · min^{-1}	↑↑CO, ↓SVR, ↓PVR
Milrinone 0.125–0.75 μg · kg^{-1} · min^{-1}	↑CO, ↓SVR, ↓PVR
Enoximone 2–10 μg · kg^{-1} · min^{-1}	↑CO, ↓SVR, ↓PVR
Levosimendan 0.05–0.2 μg · kg^{-1} · min^{-1}	↑CO, ↓SVR, ↓PVR

Abbreviations: see Figure 1 and Table 6

of vasoactive medications are summarized in Table 8 [29]. The most common drugs in daily clinical practice, such as dopamine, dobutamine, norepinephrine, or epinephrine, have a relatively low class of recommendation based on experts' opinions. Inotropes should be reserved for patients with poor vital organ perfusion. Their use differs and depends on the therapeutic goal. The ESC guidelines on AHF recommend dobutamine to increase cardiac output in patients with CS (class of recommendation IIb, level of evidence C) [2]. Norepinephrine is preferred over dopamine to maintain systolic blood pressure in the presence of persistent hypoperfusion (class of recommendation IIb, level of evidence B) [2]. Vasopressin and its analogs were shown to exert less effect on pulmonary vasoconstriction; therefore, they may be more beneficial in patients with CS and acute right HF [30].

In recent years, there has been a growing interest in landiolol, an ultra-short-acting β1-adrenergic blocker for intravenous use, with a much higher cardioselectivity (β1/β2 = 225) than esmolol. So far, the beneficial effect of landiolol on heart rate has been confirmed in patients with advanced HF and supraventricular tachycardia [31].

ECHOCARDIOGRAPHIC MONITORING OF PATIENTS ON MECHANICAL CIRCULATORY SUPPORT

Transthoracic echocardiography (TTE) and transesophageal echocardiography are widely available, reproducible, and noninvasive tools that can be used at the bedside. Therefore, they have become a standard modality to determine indications for and contraindications to the use of MCS as well as to monitor treatment outcomes. In most cases, TTE is also sufficient for monitoring and assessing the implantation of Impella 2.5 and CP devices. The correct device positioning should be confirmed by echocardiography during the procedure and then at periodic follow-up visits [10]. The monitoring of left and right ventricular function is also recommended. Moreover, TTE is also usually sufficient for monitoring patients on VA-ECMO support. In patients with long-term VAD support, echocardiographic monitoring helps identify early and long-term complications, optimize device settings, and assess improvement in myocardial function. Contraindications to MCS use that can be determined by echocardiography are presented in Table 9.

MECHANICAL VENTILATION IN PATIENTS WITH CARDIOGENIC SHOCK

Mechanical ventilation in patients with acute decompensated HF is required in the case of acute hypoxemic respiratory failure, excessive breathing effort, electrical instability, or the need for percutaneous or surgical intervention [5]. However, in patients with myocardial infarction, mechanical ventilation is associated with increased mortality (up to 50%) [32, 33].

Although a significant proportion of patients with CS complicating MI require respiratory support, there is limited evidence to indicate the ideal modality for mechanical ventilation in this population. This particularly refers to positive pressure ventilation because the inability to operate the device may lead to deterioration of the patient's clinical status. Noninvasive ventilation is widely used in conscious patients with acute systolic HF and acute respiratory failure, leading to improvement of hemodynamic, respiratory, and gas exchange parameters. Although invasive mechanical ventilation is typically used in patients with CS, noninvasive ventilation is a safe and increasingly common option for ventilatory support in conscious patients [34].

Table 9. Contraindications to mechanical circulatory support that can be assessed by echocardiography

IABP	Impella	VA-ECMO	LVAD
Aortic regurgitation Aortic dissection Peripheral atherosclerosis	LV thrombus Aortic dissection LV free wall rupture Mechanical aortic valve ASD, VSD	Aortic regurgitation Aortic dissection Thrombosis of abdominal aortic aneurysms	Unrepairable VSD Active infective endocarditis Ascending aortic aneurysm LV free wall rupture Acute right heart failure

Abbreviations: ASD, atrial septal defect; VSD, ventricular septal defect; other — see Figure 1, Tables 2 and 3

Type of shock	Potential limitations	Monitoring and treatment strategies
Hypovolemic	↓ LV and RV preload — ↓ CO and ↑ hypotension	Adequate fluid replacement, blood pressure monitoring
Cardiogenic	Although ↓ LV afterload may lead to ↑ CO, ↓ LV and RV preload may increase ↓ CO	Prevention of volume depletion
Distributive	↓ LV and RV preload - ↓ CO and ↑ hypotension	Adequate fluid replacement, blood pressure monitoring
Obstructive	↑ RV afterload may lead to rapid ↓ CO	Adequate hydration; vasopressor therapy may be required

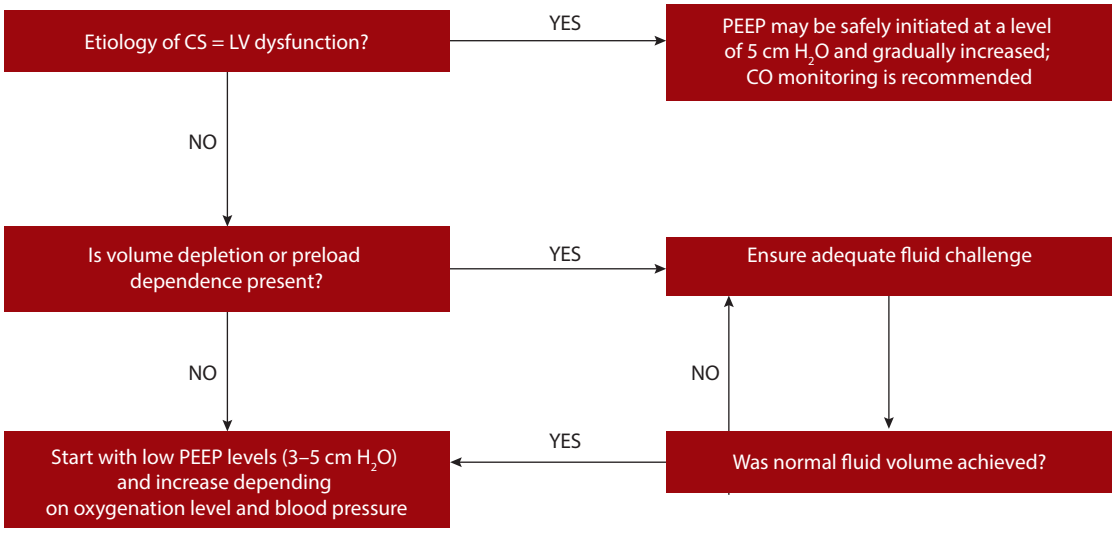

Figure 1. A summary of PEEP ventilation according to the etiology of shock, along with an algorithm for PEEP use in patients with CS
Abbreviations: CO, cardiac output; CS, cardiogenic shock; LV, left ventricle; PEEP, positive end expiratory pressure; RV, right ventricle

Table 10. Complications of mechanical circulatory support

Complication	IABP [13, 42, 43]	Impella [43–45]	VA-ECMO [46–50]
Bleeding	3.0%–3.3% (major bleeding)	8.5% (major bleeding); 17.5% (bleeding at vascular access)	15% (major bleeding)
Vascular access-induced ischemia, vascular complications	3.8%–7.5%	<4% (vascular access-induced ischemia) 9.8% (vascular complications)	10%–70%
Stroke	0.7%	<2%	17%
Sepsis/infection	15.7%	35.3%	9%
Other		tamponade, 1.7%; hemolysis, 5%–10%	kidney dysfunction, 22%; mesenteric ischemia, 9%; hemolysis, 4%

Abbreviations: see Table 2

High-flow oxygen therapy seems to be ineffective in the acute phase of CS but may be a useful option in the weaning phase, as it allows shortening of invasive ventilation [35, 36]. Continuous positive airway pressure is a rather simple technique that could be helpful during pre-hospital treatment and in low-equipped units [35]. Noninvasive pressure support ventilation is considered to be the most effective technique of noninvasive ventilation [34, 37], especially in patients with hypercapnia [38, 39].

As patients with respiratory failure are hemodynamically unstable, invasive ventilation is the most common therapeutic option in this population. Recently, the TRIUMPH study showed that a 1-hour delay in mechanical ventilation in patients with CS was associated with a significant increase in 30-day mortality [29].

The use of mechanical ventilation and moderate positive end-expiratory pressure (PEEP) levels helps achieve improved oxygenation and hemodynamic parameters in most patients with CS. However, caution should be exercised in patients with preload-dependent LV function, with right MI or volume depletion. Preload optimization is also indicated in this population. A summary of PEEP ventilation according to the etiology of shock, along with an algorithm for PEEP use in patients with CS, are presented in Figure 1.

COMPLICATIONS OF MECHANICAL CIRCULATORY SUPPORT

The most severe complications of MCS include bleeding, thromboembolic events, and, to a lesser extent, infection and hemolysis. Currently, data from randomized controlled trials comparing different MCS devices are lacking. Therefore, it is impossible to determine which of the devices offers the greatest safety or, conversely, is associated with the highest risk of complications. Available registries and meta-analyses indicate that IABP counterpulsation is most often linked to the lowest number of complications. This

refers to local complications related to vascular access, peripheral complications related to limb, central nervous system, renal, and intestinal ischemia, as well as systemic complications (infections) [10]. Impella implantation is associated with a similar or a slightly higher rate of local, peripheral, and systemic complications in comparison with IABP, while ECMO seems to have the highest complication rates (Table 10) [13, 40–50].

Article information

Conflict of interest: None declared.

How to cite: Tycińska A, Grygier M, Biegus J, et al. Mechanical circulatory support. An expert opinion of the Association of Intensive Cardiac Care and Association of Cardiovascular Interventions of the Polish Cardiac Society. Kardiol Pol. 2021; 79(12): 1399–1410, doi: 10.33963/KP.a2021.0169.

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