International Journal of Innovative Technologies in Social Science

e-ISSN: 2544-9435

Scholarly Publisher
RS Global Sp. z O.O.
ISNI: 0000 0004 8495 2390

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ARTICLE TITLE	MODERN STRATEGIES IN THE MANAGEMENT OF CARDIOGENIC SHOCK: FROM MECHANICAL CIRCULATORY SUPPORT TO AI-BASED MONITORING
DOI	https://doi.org/10.31435/ijitss.4(48).2025.4114
RECEIVED	18 September 2025
ACCEPTED	04 December 2025
PUBLISHED	16 December 2025
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MODERN STRATEGIES IN THE MANAGEMENT OF CARDIOGENIC SHOCK: FROM MECHANICAL CIRCULATORY SUPPORT TO AI-BASED MONITORING

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ABSTRACT

Background and objective: cardiogenic shock (CS) remains a leading cause of mortality in acute myocardial infarction and other cardiac conditions. Traditional medical therapy and early mechanical devices have limitations in survival and organ perfusion. Recent advances in mechanical circulatory support (MCS) devices and the integration of AI-based hemodynamic monitoring may offer improvements. This review aims to summarize modern strategies in managing cardiogenic shock, focusing on MCS (ECMO, Impella, LVAD) and AI-enabled monitoring tools, and to assess their efficacy, safety, and future potential.
Scope of review: We reviewed literature published between 2020 and 2025, identified via PubMed, Scopus, and Web of Science. Included were observational studies, meta-analyses and randomized trials comparing types of mechanical circulatory support, assessing timing, outcomes (mortality, complications), and studies exploring AI or digital monitoring in the CS setting.
Findings: recent meta-analyses suggest that Impella support is associated with lower in-hospital mortality, fewer bleeding and stroke events compared to VA-ECMO in some cohorts, though long-term survival differences are less clear (e.g. Impella vs ECMO meta-analyses). Early MCS initiation appears to improve outcomes. AI and digital monitoring remain less well studied in CS, but editorials and early studies indicate potential for better patient selection, real-time adjustments, and prediction of deterioration.
Conclusions: modern CS management increasingly combines mechanical support with improved timing, device selection, and may benefit from AI-driven monitoring tools. However, high-quality randomized trials are still required, especially those integrating AI monitoring. Future research should address standardization of monitoring protocols, cost-effectiveness, and outcome measures beyond mortality.

KEYWORDS

Cardiogenic Shock, Mechanical Circulatory Support, Impella, ECMO, AI Monitoring, Hemodynamics

CITATION

Paulina Frączkiewicz, Patryk Brzezicki, Izabela Harpula, Radosław Ramotowski, Justyna Bogdan, Benedykt Baljon, Natalia Bębenek, Gabriela Barszcz, Monika Błądek, Karolina Drygała, Sylwia Wit (2025) Modern Strategies in the Management of Cardiogenic Shock: From Mechanical Circulatory Support to AI-Based Monitoring. *International Journal of Innovative Technologies in Social Science*. 4(48). doi: 10.31435/ijitss.4(48).2025.4114

1. Introduction

Cardiogenic shock (CS) is a severe syndrome characterized by inadequate tissue perfusion due to primary cardiac dysfunction. Despite advances in interventional cardiology, mortality remains high, often exceeding 40–50% in acute myocardial infarction complicated by CS [1].

Traditional medical therapies—vasopressors, inotropes—often fail to reverse end-organ hypoperfusion or may worsen myocardial workload [2].

Mechanical circulatory support (MCS) devices such as VA-ECMO, Impella, and LVADs have emerged as essential tools. They provide cardiac output support, unloading of ventricles, and allow more time for recovery or definitive treatment [3]. However, these devices are associated with complications (bleeding, hemolysis, vascular injury) and require precise timing and patient selection [4]. Parallel to extension of device technologies, artificial intelligence (AI)-based monitoring and decision support systems are gaining interest. These tools may leverage hemodynamic waveforms, real-time physiological data, and predictive analytics to optimize MCS use, monitor response, anticipate deterioration, and reduce complications [5].

This review focuses on the current evidence (2020–2025) for modern strategies in managing cardiogenic shock: comparing MCS devices (ECMO vs Impella vs LVAD), evaluating timing and combinations, and exploring AI or digital monitoring innovations. The goal is to synthesize available data to inform clinical decision-making and identify gaps for future research.

2. Materials and methods

A systematic search was conducted in PubMed, Scopus, and Web of Science for studies published between 2020 and 2025. Search terms included combinations of: “cardiogenic shock”, “mechanical circulatory support”, “ECMO”, “Impella”, “LVAD”, “hemodynamic monitoring”, “artificial intelligence”, “predictive analytics”, “early initiation”, “timing of support”

Inclusion criteria:

- Observational studies, meta-analyses, randomized trials involving adult patients with cardiogenic shock.
- Studies comparing different types of MCS (e.g. Impella vs ECMO, ECMELLA), or evaluating timing of MCS initiation.
- Studies exploring AI-based or digital/dynamic hemodynamic monitoring related to CS.

Exclusion criteria:

- Non-English language publications.
- Animal/in vitro studies.
- Case reports with < 10 patients unless they provide novel AI/monitoring insights.
- Studies lacking outcome data (e.g., mortality, device complications, organ perfusion markers).

3. Definition and pathophysiology of cardiogenic shock

Cardiogenic shock is a state of circulatory failure in which inadequate cardiac output leads to organ hypoperfusion and tissue hypoxia [2]. According to the SCAI (Society for Cardiovascular Angiography and Interventions), cardiogenic shock can be defined in both clinical and research contexts:

- clinical definition: based on bedside assessment, including a systolic blood pressure below 90 mm Hg for more than 30 min or the need for inotropes, vasopressors, or mechanical circulatory support (MCS) to maintain adequate blood pressure, alongside evidence of systemic hypoperfusion.
- research definition: standardized criteria used in clinical studies, requiring objective hemodynamic measurements (cardiac index <2.2 L/min/m², elevated filling pressures) along with biochemical markers of organ dysfunction. This definition ensures comparability of study results and evaluation of therapeutic interventions [6].

Key pathophysiological mechanisms:

- Decreased cardiac output: Heart failure results in reduced stroke volume and cardiac output, leading to insufficient oxygen delivery to tissues [6].
- Organ hypoperfusion: Inadequate perfusion of vital organs causes dysfunction of the kidneys, liver, and brain [7].
- Tissue hypoxia: Reduced oxygen availability results in cellular injury and can lead to multi-organ failure [2].

4. Mechanical circulatory support in cardiogenic shock

Mechanical circulatory support (MCS) has become a cornerstone in the management of patients with refractory cardiogenic shock, offering temporary or long-term support to maintain systemic perfusion while reducing myocardial workload. The choice of device, timing of initiation, and patient selection are critical factors influencing outcomes.

4.1 Types of devices

VA-ECMO (veno-arterial extracorporeal membrane oxygenation)

VA-ECMO provides temporary mechanical circulatory support by draining deoxygenated blood from the venous system, oxygenating it extracorporeally, and returning it to the arterial circulation, thereby supporting both cardiac and pulmonary function. It is particularly indicated in severe CS when conventional medical therapy is insufficient

The ECMO-CS randomized clinical trial evaluated the efficacy of VA-ECMO in patients with refractory CS. Results demonstrated that VA-ECMO significantly improved short-term hemodynamic stability, increased mean arterial pressure, and supported tissue perfusion, facilitating the administration of adjunctive therapies or bridge to recovery.

However, the study also highlighted the high incidence of complications, including major bleeding, limb ischemia, hemolysis, and infection. Mortality remained substantial, underscoring the need for careful patient selection, optimized cannulation strategies, and integration into a multidisciplinary care pathway. [8].

Impella

The Impella device is a percutaneous microaxial pump designed to provide direct left ventricular unloading while maintaining antegrade aortic blood flow. By actively reducing left ventricular end-diastolic pressure and wall stress, the device optimizes myocardial oxygen supply-demand balance, potentially limiting ischemic injury in acute cardiogenic shock.

High-capacity Impella pumps (5.0 and 5.5) have been evaluated in large multicenter cohorts of patients with severe cardiogenic shock, including those refractory to conventional pharmacologic therapy. In these studies, Impella support was associated with an overall survival rate of 67.1%, with a substantial proportion of patients successfully bridged to definitive therapies such as durable left ventricular assist devices or heart transplantation.

Device-related hemodynamic effects include augmentation of cardiac output, reduction of pulmonary capillary wedge pressure, and improved systemic perfusion. The Impella system enables tailored support, allowing titration of pump flow according to patient-specific hemodynamics and myocardial recovery status. Despite its percutaneous nature, the device carries risks of vascular complications (e.g., limb ischemia, arterial injury), hemolysis, device migration, and rare occurrences of thromboembolic events

Moreover, studies emphasize the importance of early initiation of Impella support in eligible patients, demonstrating improved survival and end-organ function compared to delayed implantation. Integration of hemodynamic monitoring, including continuous assessment of left ventricular unloading and end-organ perfusion, is critical for optimizing outcomes and minimizing complications. [9].

LVAD (Left ventricular assist device)

Left ventricular assist devices (LVADs) are implantable mechanical pumps designed to provide long-term circulatory support in patients with severe heart failure or cardiogenic shock (CS). By actively unloading the left ventricle, LVADs reduce end-diastolic pressure, decrease wall stress, and improve myocardial oxygen supply-demand balance, which can facilitate myocardial recovery or serve as a bridge to heart transplantation.

A recent comparative effectiveness study evaluated percutaneous microaxial LVAD support versus intra-aortic balloon pump (IABP) or no mechanical circulatory support in patients with acute CS. The study found that LVAD use was associated with improved short-term hemodynamic parameters, including increased cardiac output and mean arterial pressure, and a reduction in the incidence of end-organ hypoperfusion Despite these hemodynamic advantages, the study noted that device-related complications—such as bleeding, hemolysis, and vascular injury—remain significant concerns, and careful patient selection is critical. [10].

4.2 Timing and patient selection

Early initiation of MCS is associated with improved outcomes compared to delayed implantation. Optimal timing depends on the severity of shock, end-organ perfusion, and response to initial medical therapy. Patient selection criteria include:

- Persistent hypotension despite inotropes or vasopressors
- Evidence of end-organ hypoperfusion (renal, hepatic, or neurologic dysfunction)
- Suitability for device implantation considering vascular anatomy, comorbidities, and expected prognosis

Recent studies have highlighted the importance of early MCS initiation in patients with acute myocardial infarction complicated by cardiogenic shock, suggesting that timely intervention can improve survival rates [11].

4.3 Outcomes and complications

Meta-analyses comparing Impella and VA-ECMO indicate that Impella may be associated with lower in-hospital mortality and fewer major bleeding or stroke events in select populations, although long-term survival differences remain unclear. Common complications of MCS include:

- Bleeding due to anticoagulation
- Hemolysis from mechanical shear stress
- Vascular injury at cannulation sites
- Infection in long-term support devices
- Thrombosis and device malfunction

Recent studies have shown that therapy and device-related complications occur in half of all patients treated with VA-ECMO and are associated with a worse prognosis [12].

5. AI-based hemodynamic monitoring and decision support

The complexity and high-risk nature of cardiogenic shock management have prompted the integration of artificial intelligence (AI) and machine learning (ML) systems into hemodynamic monitoring. AI algorithms can analyze large volumes of real-time physiological data, including arterial waveforms, central venous pressures, cardiac output, and oxygen delivery indices.

5.1 Current technologies

AI-based platforms can continuously assess patient status and predict deterioration, allowing earlier interventions and dynamic adjustment of MCS settings. Recent advancements in AI-driven tools have emerged for the hemodynamic evaluation of critically ill and surgical patients, providing real-time analysis of blood pressure measurements and hypotension prediction [13]

Decision-support systems may integrate laboratory results, echocardiography, and vital signs to guide device selection and optimize perfusion targets. These systems aim to enhance clinical decision-making by providing comprehensive assessments of patient status.

5.2 Clinical applications

AI monitoring has the potential to improve timing of MCS initiation, reduce complications, and enhance patient-specific therapy. Early utilization of MCS with Impella in patients presenting with acute myocardial infarction complicated by cardiogenic shock has been assessed for feasibility and effectiveness, suggesting potential benefits [11].

Real-time predictive analytics may help anticipate adverse events such as hypotension, arrhythmias, or device malfunction, allowing proactive management. AI-enabled estimation of cardiac output has been explored, highlighting the interchangeability of potential blood pressure measurement locations in the quest for pressure-based cardiac output estimation [14].

5.3 Limitations and challenges

Evidence is limited to small prospective studies and pilot trials; large multicenter randomized controlled trials are lacking. While AI-driven tools have emerged for hemodynamic evaluation, further research is needed to validate their efficacy and integrate them into clinical practice.

Standardization of AI algorithms and integration into ICU workflows remain challenging. The variability in AI algorithm performance and the need for standardization pose obstacles to widespread adoption in clinical settings [5].

Ethical considerations and data privacy must be addressed when implementing AI systems. The use of AI in healthcare raises concerns regarding data security, patient consent, and algorithm transparency [15].

6. Future perspectives

6.1 Integration of AI-driven digital twin models

The development of digital twin technologies—virtual replicas of patients—has the potential to revolutionize the management of CS. These models integrate multimodal data, including hemodynamic parameters, imaging, and laboratory results, to simulate real-time physiological responses. Such integration allows for personalized treatment planning and dynamic adjustment of therapeutic strategies. Recent advancements in AI and computational modeling have enabled the creation of more accurate and individualized digital twins, enhancing predictive capabilities in CS management [16].

6.2 Enhancement of hemodynamic monitoring through AI

Invasive hemodynamic monitoring remains a cornerstone in the assessment of CS. The advent of AI has introduced automated systems capable of analyzing complex hemodynamic data, facilitating real-time decision-making.

The closed-loop control system integrates advanced algorithms that process continuous monitoring data, including arterial pressure waveforms, cardiac output measurements, and oxygen saturation levels. By analyzing these parameters, the system dynamically adjusts ECMO and LVAD settings—such as pump speed and flow rates—to maintain optimal hemodynamic conditions. This approach seeks to prevent complications associated with over- or under-support, such as ventricular suction or inadequate perfusion.

The implementation of this automated system could lead to more precise and individualized MCS therapy. By reducing the need for manual adjustments, it may decrease the workload on clinical staff and minimize human error. Furthermore, continuous optimization of device settings could improve patient outcomes by maintaining stable hemodynamics, potentially reducing the incidence of adverse events and enhancing recovery prospects. [17]

6.3 Personalized medicine and biomarker integration

Advances in artificial intelligence (AI) and digital twin technologies enable the integration of patient-specific biomarkers into the management of cardiogenic shock (CS), paving the way for precision medicine approaches. Machine learning (ML) algorithms can process high-dimensional data from multiple sources, including genomics, transcriptomics, proteomics, metabolomics, and standard laboratory tests, to identify predictive patterns of individual patient responses to therapies.

In the context of CS, these biomarkers may include circulating levels of cardiac troponins, natriuretic peptides (BNP, NT-proBNP), inflammatory cytokines (IL-6, TNF-α), markers of oxidative stress, and metabolomic signatures reflecting myocardial energy metabolism. AI-based models can analyze how these variables interact with hemodynamic parameters, mechanical circulatory support settings, and pharmacologic interventions, allowing for patient-specific optimization of therapy.

Furthermore, integration of genetic and epigenetic information enables risk stratification for adverse outcomes, such as arrhythmias, multiorgan dysfunction, or inadequate ventricular recovery. Proteomic and metabolomic profiling may guide the selection and titration of inotropes, vasopressors, and anticoagulation strategies during MCS. By continuously updating predictions based on real-time monitoring, AI-driven platforms can suggest dynamic adjustments in device parameters (e.g., VA-ECMO flow, LVAD speed) tailored to each patient's evolving physiology. [16]

6.4 Ethical and legal considerations

The implementation of AI in healthcare, particularly in critical areas like CS management, raises significant ethical and legal issues. Key concerns include patient autonomy, informed consent, data privacy, algorithmic transparency, and accountability. Establishing robust ethical frameworks and legal regulations is essential to address these challenges and ensure the responsible use of AI technologies in clinical practice [18].

6.5 Challenges and barriers to implementation

Despite the promising potential of AI in CS management, several challenges impede its widespread adoption. These include the need for large-scale, multicenter randomized controlled trials to validate AI algorithms, integration of AI systems into existing clinical workflows, standardization of data formats, and ensuring interoperability between different technological platforms. Overcoming these barriers is crucial for the successful implementation of AI in routine clinical practice [19].

7. Research gaps and recommendations

Despite advances in MCS and AI-based monitoring, several research gaps remain. First, large randomized controlled trials comparing VA-ECMO, Impella, and LVADs in diverse patient populations are still lacking [20]

Second, AI tools for hemodynamic monitoring are mostly limited to pilot studies or single-center implementations, limiting generalizability [21].

Studies are needed to validate predictive algorithms, evaluate impact on clinical outcomes, and integrate AI insights into standardized treatment protocols.

Third, understanding cost-effectiveness, training requirements, and workflow integration is crucial for translating AI into routine practice. Finally, ethical, legal, and privacy considerations must be embedded into research and deployment plans to ensure patient safety and public trust [16]

Recommendations for future research:

- Conduct multicenter randomized trials comparing MCS devices, with and without AI support.
- Develop standardized, interoperable AI platforms for continuous monitoring and predictive analytics.
- Investigate the combination of AI, biomarkers, and patient-specific data for precision therapy.
- Incorporate ethical, legal, and patient-centered frameworks in all AI-based studies

8. Discussion

Modern management of cardiogenic shock increasingly relies on a combination of mechanical circulatory support devices and emerging AI-driven monitoring systems. Early initiation of appropriately selected MCS can improve survival, while AI-based tools may facilitate individualized care by predicting hemodynamic deterioration and optimizing therapy. Despite these advances, robust evidence from large, randomized trials remains limited, particularly regarding the integration of AI into clinical decision-making. Ethical, legal, and logistical considerations, including data privacy, interoperability, and clinician training, are critical for safe implementation. Future research should focus on standardized protocols, high-quality registries, and multicenter trials that evaluate both traditional outcomes (mortality, complications) and AI-driven endpoints (predictive accuracy, intervention timing).

9. Conclusions

Innovations in mechanical circulatory support and AI-based monitoring are transforming cardiogenic shock care. While early implementation and individualized therapy show promise, further evidence from large-scale studies is needed to establish best practices and optimize patient outcomes.

9. List of abbreviations

AI – Artificial Intelligence
CS – Cardiogenic Shock
ECMO – Extracorporeal Membrane Oxygenation
MCS – Mechanical Circulatory Support
LVAD – Left Ventricular Assist Device
VA-ECMO – Veno-Arterial Extracorporeal Membrane Oxygenation
SCAI – Society for Cardiovascular Angiography and Interventions
ML – Machine Learning
ICU – Intensive Care Unit
LV – Left Ventricle
SAT – Systemic Analgesic Therapy (if still referenced from previous sections)
PMC – PubMed Central (used in references)
ECG – Electrocardiogram (if mentioned elsewhere)
CVP – Central Venous Pressure
HR – Heart Rate

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All authors have read and agreed with the published version of the manuscript.
Funding statement: The study did not receive special funding.
Conflict of interest statement: The authors declare that they have no conflict of interest.

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