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Miniaturized Extracorporeal Circuits: Innovative Approaches in Cardiac Surgery
Miniatürize Ekstrakorporeal Devreler: Kardiyak Cerrahide Yenilikçi Yaklaşımlar

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ÖZET

Minimal İnvaziv Ekstrakorporeal Dolaşım (MiECC) sistemleri, konvansiyonel kardiyopulmoner bypass ile ilişkili hemodinamik bozuklukları, sistemik inflamatuar yanıtı ve perioperatif komplikasyonları azaltmak amacıyla geliştirilmiş ileri düzey perfüzyon teknolojileridir. Kapalı devre, heparin kaplı ve miniatürize tasarıma sahip olan MiECC, venöz rezervuar içermez, priming hacmini minimize eder ve kanın yapay yüzeylerle temasını azaltarak sistemik inflamatuar yanıtın kontrolünü sağlar. Ayrıca, optimize edilmiş devre tasarımı perioperatif hematokrit seviyelerinin korunmasına, oksijen taşıma kapasitesinin sürdürülmesine ve transfüzyon gereksiniminin azalmasına katkıda bulunur.

MiECC'de kullanılan teknik iyileştirmeler arasında yalnızca kanla temas halinde aktive olan aspirasyon sistemleri, postoperatif ototransfüzyon için hücresel kan geri kazanım (cell saver) sistemleri ve modüler devre tasarımları öne çıkar. Klinik çalışmalar ve meta-analizler, MiECC kullanımının postoperatif morbiditeyi azalttığını, böbrek ve miyokard fonksiyonunu koruduğunu ve inflamatuar belirteçlerde düşüş sağladığını göstermektedir. Kapalı devre ve düşük priming hacmi sayesinde heparin ihtiyacı azalmakta, kanama riski minimize edilmekte ve hasta güvenliği artmaktadır. Bu derlemede, MiECC sistemlerinin teknik özellikleri, uygulama yöntemleri ve klinik avantajları güncel araştırma bulguları ışığında ayrıntılı şekilde ele alınmış, kardiyak cerrahideki potansiyel rolü ve faydaları vurgulanmıştır.

Anahtar Kelimeler: Minimal invaziv ekstrakorporeal dolaşım, Kardiyopulmoner bypass, Perfüzyon teknolojisi, Organ koruması, Kardiyak cerrahi

ABSTRACT

Minimal Invasive Extracorporeal Circulation (MIECC) systems are advanced perfusion technologies developed to reduce hemodynamic disturbances, systemic inflammatory response, and perioperative complications associated with conventional cardiopulmonary bypass. MIECC features a closed, heparin-coated, miniaturized circuit without a venous reservoir, minimizing priming volume and reducing blood contact with artificial surfaces, thereby controlling systemic inflammatory response. Optimized circuit design also contributes to the preservation of perioperative hematocrit levels, maintenance of oxygen-carrying capacity, and reduction of transfusion requirements. Technical improvements in MIECC include blood-activated suction devices, cellular blood recovery (cell saver) systems for postoperative autotransfusion, and modular circuit designs. Clinical studies and meta-analyses have shown that MIECC reduces postoperative morbidity, preserves renal and myocardial function, and decreases inflammatory markers. The closed circuit and low priming volume further reduce heparin requirement, minimize bleeding risk, and enhance patient safety. This review details the technical characteristics, application methods, and clinical advantages of MIECC systems, highlighting their potential role and benefits in cardiac surgery based on current evidence.

Keywords: Minimal ınvasive extracorporeal circulation, Cardiopulmonary bypass, Perfusion technology, Organ protection, Cardiac surgery

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INTRODUCTION

Since the advent of open-heart surgery in the early 1950s, a series of significant scientific and technological advancements have transformed cardiac surgery into a routine intervention for the treatment of heart diseases. Improvements in surgical techniques, anesthesia management, intensive care practices, and perfusion technologies have markedly enhanced clinical outcomes. Yet, cardiac surgery continues to be associated with appreciable morbidity and mortality, most prominently in procedures classified as complex or high risk.Findings from the Society of Thoracic Surgeons (STS) registry, the world's largest cardiac surgery database encompassing over 200,000 procedures, demonstrate that outcomes for low-risk elective interventions such as CABG, isolated AVR, or mitral valve repair remain excellent, independent of the surgical technique utilized (1).

Conventional cardiopulmonary bypass systems (CCPB) and off-pump coronary artery bypass grafting (OPCABG) have been widely compared in previous studies (2). CCPB, however, is associated with hemodynamic disturbances, systemic inflammatory responses, and increased perioperative blood transfusion requirements, which pose significant limitations, particularly in minimally invasive surgical procedures. To overcome these challenges and enhance safety in minimally invasive interventions, minimal invasive extracorporeal circulation (MIECC) systems have been developed. By utilizing a closed, heparin-coated, and miniaturized circuit design, MIECC reduces priming volume and hemodilution, minimizes blood contact with artificial surfaces, and modulates the systemic inflammatory response. These characteristics enhance the effectiveness of organ-protective mechanisms both intraoperatively and postoperatively, decrease the need for blood transfusions, and help limit complications.

MIECC mitigates systemic inflammatory response syndrome (SIRS) by limiting the blood–air interface, reducing the length of artificial tubing, and enhancing biocompatibility through complete heparin coating of the circuit. Further benefits of MIECC include reduced hemodilution during cardiopulmonary bypass (CPB), preservation of higher hematocrit levels, decreased transfusion requirements for blood and blood products, and minimized postoperative blood loss. In this review, the technical characteristics, clinical applications, and impacts of MIECC systems in cardiac surgery are comprehensively examined. The literature search was conducted through the PubMed, Scopus, Web of Science, and Google Scholar databases, and studies published between 2000 and 2025 were evaluated. Search terms included "Minimal Invasive Extracorporeal Circulation," "miniaturized cardiopulmonary bypass," "MIECC systems," "cardiac surgery," "organ protection," and "systemic inflammatory response."

The included studies comprise randomized controlled trials, prospective and retrospective clinical investigations, meta-analyses, and preclinical experimental research. The selection criteria encompassed the technical design of MIECC, its intraoperative and postoperative effects, as well as comparisons with conventional CCPB. A total of 40 studies were incorporated into this review, and the data were synthesized with respect to the technical characteristics of MIECC, its clinical advantages, organ-protective effects, and its impact on the inflammatory response.

The Role and Significance of MIECC

The conventional extracorporeal circuit incorporates arterial and venous conduits, a venous reservoir, pumping units, an oxygenator, a heat exchanger, vent and cardiotomy reservoirs, aspiration systems, filtration modules, ultrafiltration equipment, and a cardioplegia administration system. Despite the routine and widespread application of these traditional configurations, meaningful technological advancement has been limited (3). In order to highlight the need for optimal intraoperative perfusion in cardiac surgery, nearly a decade ago one of the most authoritative textbooks in the field, *On Bypass: Advanced Perfusion Techniques*, stated: "Over the past 50 years, the evolution of perfusion technology has occurred only to a limited extent, primarily because of a lack of financial resources or insufficient incentives to further advance the technology" (4).This prediction has materialized with the advent of MIECC technology. Over the past decade, advances in miniaturized CPB systems have been standardized by the International Society for Minimal Invasive Extracorporeal Technologies (MiECTiS). By consolidating diverse mini-CPB practices that had emerged with varying designs and terminology, MiECTiS has succeeded in establishing a systematic framework. Today, MIECC is recognized as a well-established technology that integrates all advancements in modern perfusion science. The configuration comprises a closed extracorporeal circuit with biologically inert blood-contact interfaces and reduced priming demands, accompanied by a centrifugal pump, a membrane-based oxygenator, a heat-exchange module, a venous air-removal or bubble-trapping system, a cardioplegia unit, and a dedicated device for managing shed blood.

One of the most significant developments in MIECC systems over the past decade has been their evolution from type I to type IV designs. The currently employed fourth-generation hybrid modular MIECC system incorporates a rigid-shell venous reservoir, allowing rapid conversion to an open circuit in emergency situations, thereby addressing unexpected intraoperative scenarios and all associated safety concerns. These features enable MIECC to

provide a safe and adaptable approach suitable for all types of cardiac surgery cases (Figure 1) (5).

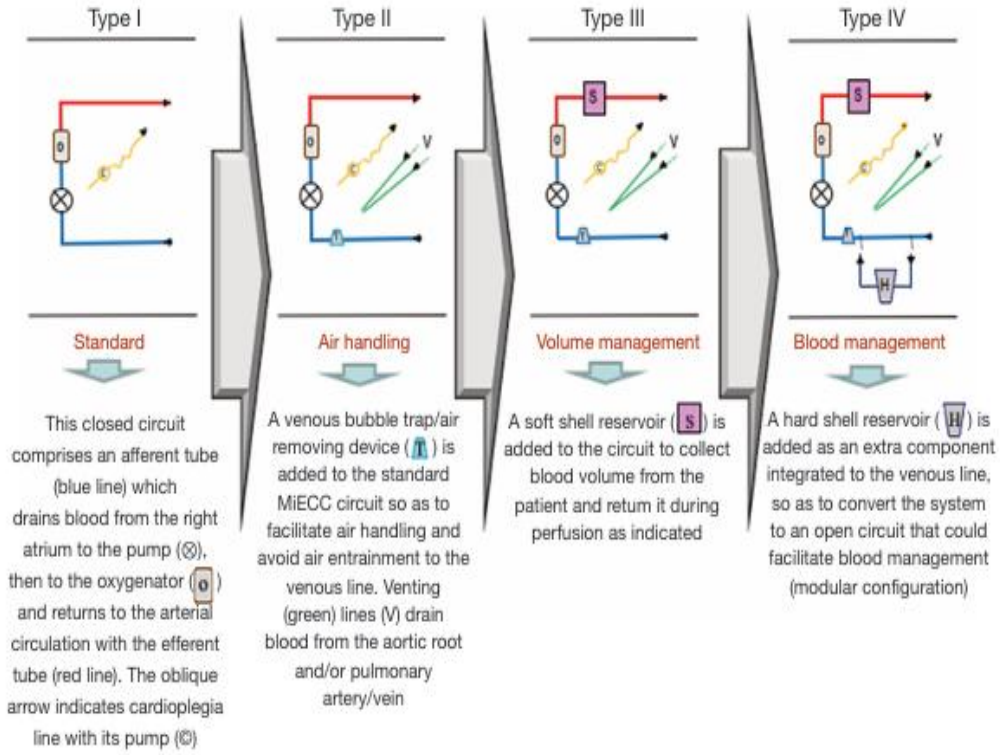

Figure 1. Established classification of MIECC circuits. X, pump; O, oxygenator; C, cardioplegia; T, bubble-trap/air removing device; V, vent (aortic/pulmonary); S, soft-bag/reservoir; H, hard-shell/reservoir; MIECC, minimal invasive extracorporeal circulation (5).

Characteristics of Minimal Invasive Extracorporeal Circuits

Once referred to as Simplified Bypass Systems (SBS) or Minimally Invasive Extracorporeal Circuits, MIECC is currently applied to facilitate kinetic-assisted venous drainage (KAVD) and maintain systemic perfusion pressure through a closed veno-arterial circuit powered by a single centrifugal pump. With this design, the patient assumes the role of the reservoir, and the priming volume in adults commonly measures 400–500 ml. Because MIECC systems operate with a closed-circuit configuration and reduced reservoir capacity, vacuum-assisted venous drainage (VAVD) has become an important supportive component in many contemporary designs. By applying controlled negative pressure to the venous line, VAVD enhances venous return, stabilizes pump preload, and facilitates adequate flow during minimally invasive cardiac procedures where gravitational drainage may be insufficient. Therefore, although not universally mandatory in all configurations, VAVD is frequently integrated into modern MIECC platforms to maintain hemodynamic stability and optimize circuit performance.

Even though the tubing diameters are similar to those in conventional CCPB circuits, the significant reduction in overall circuit length minimizes the blood–surface interaction and consequently lowers the probability of an inflammatory response intraoperatively. Furthermore, MIECC systems offer advantages such as reduced hemodilution and attenuation of the systemic inflammatory response, while also enabling decreased activation of coagulation cascades, potential reduction in microbubble formation, limited postoperative morbidity, and improved blood conservation (6). In order to standardize these developments and promote research, the International Society for Minimal Invasive Extracorporeal Technologies (MiECTiS) was established in 2015. In a position statement published by MiECTiS, it was indicated that a MIECC system must possess at least Type II circuit characteristics among the four defined circuit types (Figure 2) (7).

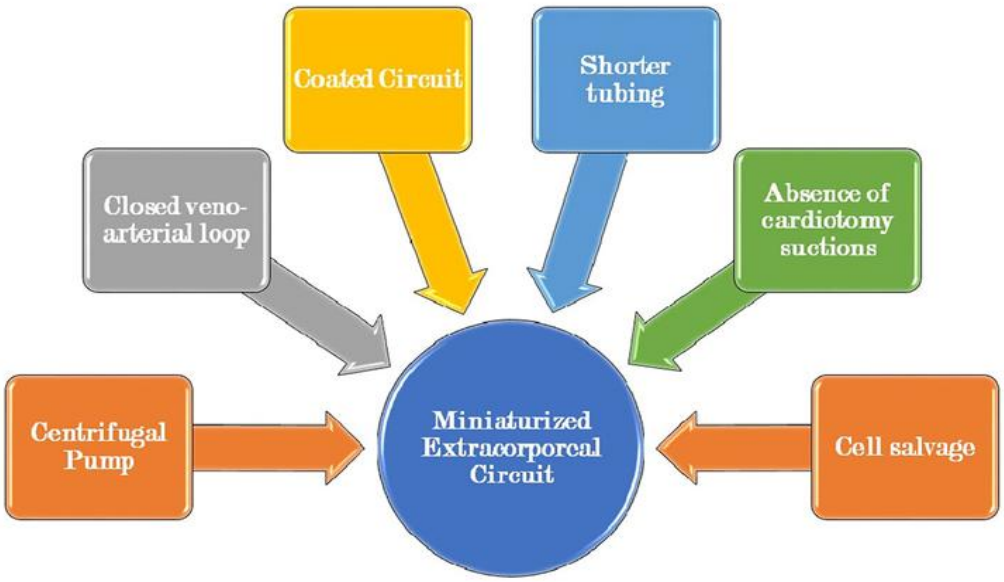

Figure 2. Key components of a MIECC circuit and differences from a conventional CPB circuit (7).

Originally, the MIECC concept evolved from an ECLS circuit configured for CABG, incorporating the capability of delivering cardioplegia (Type I). A complete system should encompass a closed and compact CPB circuit, biocompatible blood-contact surfaces, reduced priming volume, a centrifugal pump, a membrane oxygenator, a venous air-removal device, and a blood management platform enabling supplementary cardioplegia administration.

According to early MIECC concepts, certain components such as large venous reservoirs or cardiotomy suction systems were minimized or omitted to reduce priming volume and circuit complexity. However, the presence or exclusion of a heat exchanger is not a universal requirement in MIECC systems and may vary depending on circuit design and clinical

application. Additional components that may be integrated into these MIECC systems include an arterial line filter, aortic root vent, pulmonary venous vent, pulmonary arterial vent, and soft bag/soft reservoir (8). Some reports mention the possibility of adding a hard-shell reservoir or an intelligent suction device to enhance safety and facilitate application (9). MIECC was initially employed in on-pump CABG procedures. Kowaleski and colleagues conducted a comprehensive Bayesian network meta-analysis encompassing 134 randomized controlled trials with a total of 22,778 patients, comparing the safety and efficacy of MECC with off-pump CABG (OPCABG) and conventional on-pump CABG. They concluded that the use of MIECC systems, as well as OPCAB, could improve perioperative outcomes.

The modifications of the miniaturized extracorporeal circulation circuit and the physiological benefits provided by its components are presented graphically in Figure 3 (10).

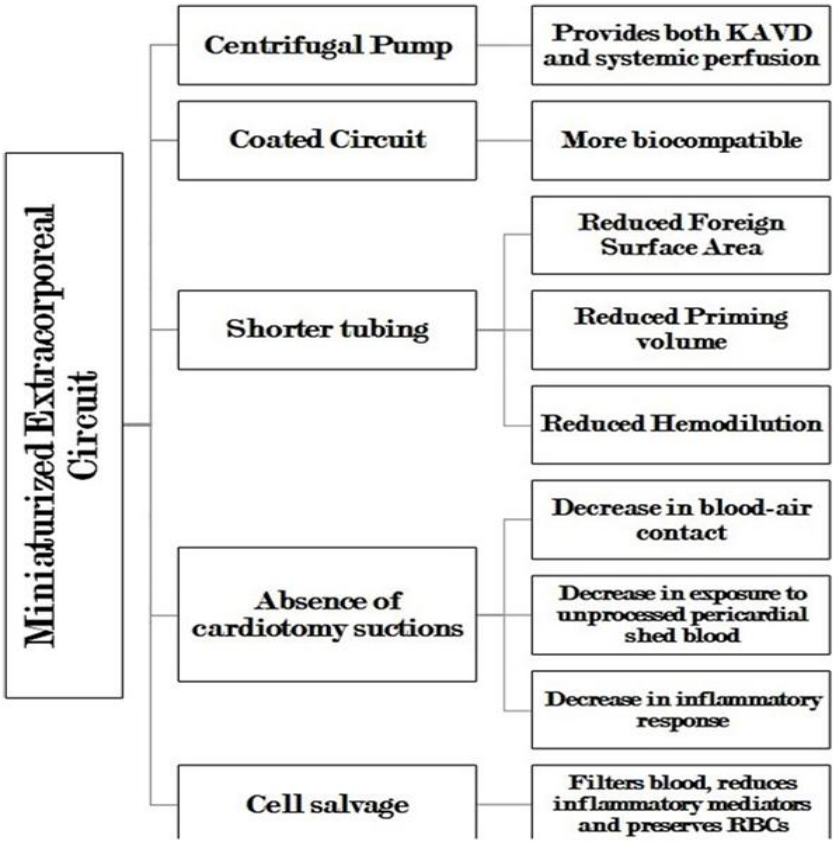

Figure 3. Physiological benefits of MIECC circuit modifications and components (10).

Clinical Evidence Supporting MIECC

Effects on the Cardiovascular System;

Conventional CPB circuits may contribute to myocardial injury through non-pulsatile roller pump mechanics, cardiotomy suction effects, hypothermia, cardioplegia, and intraoperative hypoperfusion. In addition, postoperative myocardial damage may arise from surgical manipulation, ischemia associated with aortic cross-clamping, and subsequent reperfusion injury. In 2005, Karamlou and colleagues investigated a miniaturized extracorporeal circuit using an asanguineous priming strategy in an experimental infant model. Their findings demonstrated that reducing circuit surface area and eliminating blood-air interaction attenuated neutrophil-mediated inflammatory responses and supported improved cardiopulmonary function following cardiopulmonary bypass. These physiological improvements suggested potential benefits in myocardial recovery associated with miniaturized circuit technology (11).

In a 2009 randomized controlled trial conducted by Castiglioni and colleagues, 120 patients undergoing isolated aortic valve replacement were assigned to either a MIECC system or conventional CPB. The results demonstrated that the MIECC group exhibited superior postoperative outcomes compared to the standard CPB group in terms of transfusion requirements, platelet consumption, and myocardial injury. Specifically, the MIECC group had lower drainage volumes and higher platelet counts, while no significant differences were observed in mortality or length of hospital stay. Serum cardiac troponin I (cTn-I) levels were also significantly lower in the MIECC group (12).

Similarly, a 2012 study by Liu and colleagues involving 40 patients undergoing CABG surgery showed that the use of MIECC maintained lower cTn-I levels compared to conventional CPB. Measurements were taken after anesthesia induction, 30 minutes after the initiation of CPB, and at 2, 6, 12, and 24 hours postoperatively. In the MIECC group, cTn-I levels at 2, 6, and 12 hours were significantly lower ($p < 0.01$) (13).

In a multicenter study conducted by Farag and colleagues, two different MIECC systems were compared with conventional CPB. Cytokine levels, including IL-1β, IL-6, IL-10, TNF-α, migration inhibitory factor, and CD40 ligands, were measured during the first 24 hours post-procedure in 60 consecutive patients, who were randomized into three groups. In both MIECC groups, levels of the cardiac biomarker CK-MB were lower compared to the CCPB group (20.64 vs. 28.18), indicating more effective cardioprotection during surgery (14).

Moreover, another advantage of the MIECC system is the ability to modify cardioplegia administration techniques. Using the “Calafiore technique,” concentrated warm cardioplegia

is directly mixed with blood and administered intermittently, thereby minimizing hemodilution. This technique was successfully implemented in 48 patients using the modular MIECC system at Ulm University in Germany (15).

Recently, it has been suggested that mitochondrial DNA (mtDNA) may act as a damage-associated molecular pattern (DAMP) and be linked to the activation of local inflammatory responses. In a clinical study conducted by Zajonz and colleagues involving 45 patients, plasma mtDNA levels in the MIECC group were found to be significantly lower compared to the CCPB group, and this was associated with a reduced incidence of postoperative atrial fibrillation (16).

Effects on the Respiratory System

According to a comprehensive review by Apostolakis and colleagues, which addressed strategies to prevent intraoperative lung injury during cardiopulmonary bypass, the biocompatible and heparin-coated surfaces used in MIECC systems significantly reduce intrapulmonary shunting and markedly improve respiratory indices (pO_2/FiO_2). Furthermore, the reduced activation of pulmonary capillary endothelial cells provides additional benefits to lung function.

In addition, the use of a controlled suction system or a cell saver device in combination with a low priming volume shortens the contact time of blood with extravascular tissues and air, thereby limiting hemodilution and the inflammatory response. Consequently, complications are reduced, and postoperative respiratory and lung functions are improved (17).

Effects on Renal Function

Bennett and colleagues retrospectively analyzed CABG patients who underwent either MIECC or conventional CPB (CCPB) ([MIECC: n = 120; CCPB: n = 120]) to investigate the impact of MIECC on renal function. The study found that periodic venous return restrictions in the MIECC circuit reduced mean flow; however, due to decreased hemodilution, organ perfusion was comparable in both systems, and mean oxygen delivery was equal (18).

Additionally, in a randomized controlled study by Yuruk and colleagues (n = 20), serum creatinine, NGAL levels, and creatinine clearance rates were measured during MIECC use and up to five days postoperatively. The results demonstrated that the MIECC circuit did not adversely affect renal function (19).

Effects on Neurocognitive Protection

In 2005, Karamlau and colleagues conducted a study in neonatal pigs (n = 20; MIECC: 10, CCPB: 10) and demonstrated that the use of a miniaturized circuit significantly modulated the inflammatory response and enhanced cerebral protection by preventing the

cerebrovascular “no-reflow” phenomenon observed during deep hypothermic circulatory arrest (DHCA) and hypothermic low flow (HLF) (20).

Similarly, in a human study by Bennett and colleagues (n = 80), the effects of hemodilution and bypass flow rates on cerebral desaturation were examined. Near-infrared spectroscopy (NIRS) measurements of oxyhemoglobin and tissue oxygenation index (TOI) revealed that patients in the conventional CPB group experienced longer and more severe episodes of cerebral desaturation (21).

In a larger study conducted by Remadi and colleagues (n = 400; MIECC: 200, CCPB: 200), similar results were observed, with MIECC use being associated with a significant reduction in neurological complications (22). Other studies have also demonstrated that reducing hemodilution helps prevent cerebral hypoperfusion, thereby providing protection against stroke and other neurological events. Furthermore, MIECC has been reported to decrease cerebral gas microembolism and preserve organ function. Collectively, these findings support the consideration of MIECC as a safe and effective approach to minimize neurocognitive impairment (23).

Effects on Hematologic Protection

CCPB can lead to various hematologic complications, including anemia, hemolysis, coagulopathy, and platelet dysfunction, primarily due to hemodilution. During CPB, mixing the circuit priming volume with the patient’s blood can lower hematocrit below 23%, resulting in interstitial edema in vital organs such as the brain, lungs, and heart, which in turn may cause tissue ischemic injury and organ dysfunction (24).

Randomized controlled trials have shown that MIECC better preserves hematocrit and hemoglobin levels, while fibrinogen and platelet counts remain more stable compared to CCPB. Thanks to its low priming volume and centrifugal pump, MIECC reduces hemolysis and minimizes free hemoglobin levels. This, in turn, decreases the need for blood transfusions and lowers the risk of transfusion reactions. MIECC offers particular advantages for patients who refuse homologous blood products, such as Jehovah’s Witnesses, and for those with a low body surface area. For example, John and colleagues reported successful outcomes using MIECC in seven cases (six CABG, one aortic valve replacement) (25).

Effects on the Inflammatory Response

The systemic inflammatory response that emerges in the early period after CPB is considered a significant disadvantage. This response can lead to hemodynamic instability, multiple organ dysfunction, and prolonged intensive care and hospital stays. The primary cause is the contact

of blood with air and the artificial surfaces of the CPB circuit, as well as surgical trauma, ischemia, and reperfusion.

These processes trigger the activation of proinflammatory cytokines and the complement system, leading to neutrophil activation. In addition, ischemia/reperfusion injury increases thrombin accumulation and the release of IL-1, IL-6, and IL-8 cytokines. The reinfusion of pericardial fluid also affects inflammation and hemostasis, as this fluid contains proinflammatory mediators and damaged red blood cells. The MIECC system, through its short circuit length, biocompatible coating, and centrifugal pump, reduces these adverse interactions and minimizes damage to red blood cells (26).

In patients undergoing MIECC, inflammatory markers such as IL-10, TNF-alpha, C3a, and CD11b have been found at lower levels compared to conventional CPB. This benefit is attributed to reduced thrombin generation, which diminishes the key link between inflammation and coagulation. Consequently, MIECC is less inflammatory, accelerates postoperative recovery, and reduces long-term risks (27, 28).

Postoperative Clinical Outcomes

Clinical experience with MIECC demonstrates that patients generally experience less postoperative chest drainage and require shorter periods of mechanical ventilation and ICU care. Moreover, the markedly reduced need for blood transfusions during and after surgery in MIECC cases helps minimize the likelihood of transfusion-related adverse events. Additionally, the incidence of postoperative atrial fibrillation is lower in MIECC patients compared to those receiving CCPB. Collectively, these findings suggest that the MIECC system may offer superior postoperative morbidity outcomes compared to CCPB (29).

Mortality Outcomes

Although MIECC has been associated with various perioperative benefits, the literature consistently indicates that it offers no measurable advantage or disadvantage over standard CCPB in terms of intraoperative mortality. Additionally, two published studies by Puehler and colleagues, including a total of 2,243 patients, demonstrated that 30-day overall mortality after CABG performed with the MIECC system was significantly lower than with CCPB.

Similarly, meta-analyses of various randomized controlled trials (RCTs) also report results in favor of MIECC. In light of these findings, the established and potential clinical benefits of MECC use are summarized in Figure 4 (30, 31).

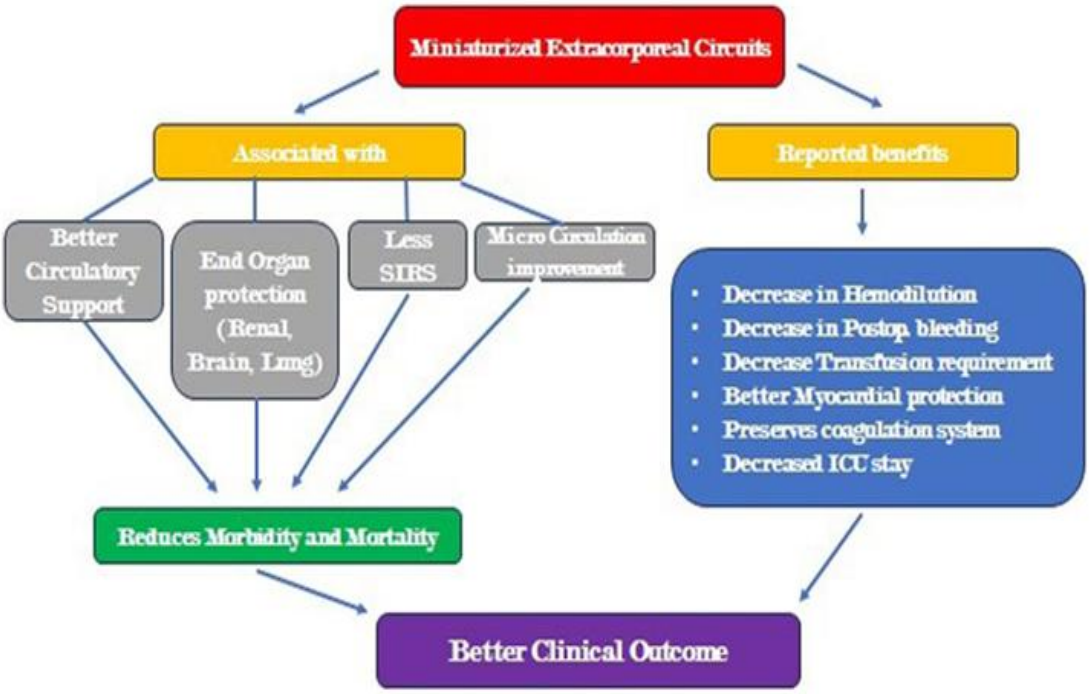

Figure 4. Proven and Potential Clinical Benefits Associated with Miniaturized Extracorporeal Circulation (30, 31)

Miniaturized Extracorporeal Circulation Systems: Historical and Contemporary Platforms

1. CardioVention CORx System (MIECC Type I; Historical, Discontinued Platform)

The CORx system was one of the early commercially available concepts in miniaturized extracorporeal circulation; however, it is no longer commercially available and should be regarded as a historical platform rather than a current clinical system.

The CORx system, developed by CardioVention (Santa Clara, CA), is the first commercially available miniaturized extracorporeal circulation system. Designed as a single-use, compact veno-arterial (VA) circuit, the system incorporates a kinetic-assisted pump, oxygenation, air removal, and coarse filtration capabilities. In a long-term perfusion study conducted by Mueller and colleagues using a bovine model (n = 12), the CORx system was compared with conventional CPB. The findings indicated that the CORx system reduced hemodilution, improved gas exchange, limited platelet loss due to the reduced surface area, and did not induce hemolysis during six hours of full-flow perfusion (32).

2. COBE/Sorin Synergy System (MIECC Type I configuration)

The COBE/Sorin Synergy System, developed by COBE Cardiovascular Inc. (Arvada, CO), is a compact circuit that integrates oxygenation, filtration, and air removal functions with a centrifugal pump. Unlike conventional systems, the venous line connects directly to the

centrifugal pump, eliminating the need for a venous reservoir, limiting blood-air contact, and reducing priming volume. The system can be complemented by a vacuum bag that collects blood returning only from the right superior pulmonary vein and the ascending aorta vents. Through the aspiration system, only partial blood-air contact occurs, which is why the system is considered "semi-closed."

An ultrasound probe is integrated on the venous side to detect air entry, and perfusion is immediately stopped if air is detected. Colli and colleagues (n = 53) and Huybregts and colleagues successfully utilized MIECC in AVR and mitral valve repair cases, respectively (33).

3. Getinge (formerly Maquet) – MECC System (MIECC Type III configuration)

The MECC system, historically associated with the Maquet brand (now under Getinge), features a compact, closed-circuit design that prevents blood–air contact and eliminates the need for an open venous reservoir. The system consists of a centrifugal Rotaflow pump, a polymethylpentene Quadrox D membrane oxygenator, a heat exchanger, a VBT160 venous air trap positioned between the venous line and pump, an arterial filter, and a 1000 ml closed bag for priming and volume replacement during the procedure. All components are heparin-coated.

Clinical studies have shown that patients treated with this miniaturized ECC system exhibit significantly lower levels of inflammatory markers compared to conventional CPB. In a study including 60 patients (MECC: 30; CCPB: 30), Fromes and colleagues reported a reduced inflammatory response in the MECC-treated group relative to the standard CPB group. Based on these findings, the authors recommended the use of this MECC configuration to maintain total extracorporeal circulation (34).

4. Terumo ROCsafeRX MPC System (MIECC Type II configuration)

The ROCsafeRX™ MPC, developed by Terumo Cardiovascular Systems (MI, USA), consists of a Sarns™ centrifugal pump, a Terumo RX 15 hollow-fiber oxygenator, and a Pall AL8x arterial line filter.

Notable features include an Air Bubble Detector (ABD), a BT15X bubble trap, and an Electronic Venous Occluder (EVO) integrated within the venous line. The system is specifically designed for venous air removal. Functionally, the ABD detects air in the venous line and immediately sends a signal to the centrifugal pump, reducing the pump speed to 1500 rpm to prevent forward or reverse flow. Subsequently, the EVO selectively partially occludes the venous line in coordination with the pump flow rates, ensuring effective air management.

Additionally, the system includes a vertical venous reservoir designed for emergency use, allowing seamless conversion from a closed to an open circuit. Quick-connect components, integral to the circuit, facilitate this transition. The system is also commonly paired with a cell saver device to manage perioperative blood loss. All components are coated with X-coating to enhance the circuit's biocompatibility (35).

5. Terumo ROCsafeRX MPC System (MIECC Type II configuration)

The Capiox system, developed by Terumo in Tokyo, Japan, is a closed miniaturized circuit. The system includes an SP45X centrifugal pump, a Capiox RX 25 oxygenator with a closed-layer reservoir, and a PMEA (poly-2-methoxyethyl acrylate)-coated circuit designed to minimize protein and blood cell adsorption and desaturation.

In a study conducted by Ohata and colleagues, patients treated with the Capiox mini system demonstrated significantly lower levels of IL-8 and neutrophil elastase, reduced blood loss, and less hemodilution compared to those receiving conventional CPB. The researchers also reported the system's benefits in supporting blood conservation (36).

6. LivaNova (formerly Sorin Group) – Extracorporeal Circulation Optimized System (ECCO) (MIECC Type IV configuration)

The Extracorporeal Circulation Optimized System (ECCO), currently marketed under LivaNova (formerly Sorin Group, Italy), is a fully miniaturized cardiopulmonary bypass system. The platform includes a centrifugal priming pump, a 1.1 m² hollow-fiber oxygenator, a low-priming-volume arterial filter, a pre-bypass filter, a soft-shell reservoir (SSR) intermittently isolated near the systemic circulation, and a cell saver device.

In the SSR configuration, two separate lines are incorporated: one dedicated to aortic root venting and the other to left ventricular decompression. The system's side inlet creates a centrifugal flow pattern that directs entrained air toward the central upper region of the filter chamber. When air is detected, the ultrasonic air bubble detector (ABD) triggers the roller pump, enabling air evacuation through the superior port of the 120-µm side-inlet filter. In a multicenter investigation by Momin et al. involving 49 patients, this ECCO configuration was reported to be both safe and feasible for use in major aortic surgical procedures (37).

7. Eurosets – Landing and ECMOlife Systems (MIECC Type IV configuration)

Eurosets has recently introduced contemporary minimized extracorporeal circulation platforms such as the Landing system and ECMOlife integrated circuits, representing a newer generation of compact extracorporeal technologies. These systems emphasize reduced priming volume, improved biocompatibility coatings, modular safety configurations, and enhanced air management strategies. Compared with earlier MECC designs, Eurosets

platforms integrate modern perfusion concepts including hybrid closed-circuit flexibility and improved ergonomics for minimally invasive cardiac surgery. Recent clinical observations suggest that these newer systems aim to optimize inflammatory response control, facilitate rapid conversion strategies, and enhance intraoperative safety management, reflecting the ongoing evolution of MIECC technology.

Risks and Safety Measures in the Use of MIECC

The MIECC system, developed for minimally invasive cardiac surgery (MICS), was initially compared with OPCABG procedures. During early applications, concerns arose regarding air management features and the potential risk of systemic air embolism. Moreover, the absence of a venous reservoir and arterial microfilters posed additional limitations. In vitro studies have demonstrated that MIECC systems without a venous reservoir exhibit 8–10 times more microemboli in the arterial line compared to conventional CPB. Clinical studies have reported occasional venous air management issues; however, these events did not lead to significant adverse clinical outcomes.

Furthermore, MIECC systems present certain constraints in managing excessive venous return and providing immediate volume infusion. When cardiotomy aspiration is required, a separate cell saver device is necessary, and some systems lack a heat exchanger. Therefore, anesthesiologists must be prepared to manage intravascular volume and temperature effectively.

To address these concerns, manufacturers have incorporated advanced air elimination technologies and sensitive bubble detectors into the systems. Additionally, some surgical teams have attempted to overcome limitations by employing supplementary venous and cardiotomy reservoirs, arterial filters, and heat exchangers. The integrated hard-shell venous reservoir in 4th-generation hybrid modular MIECC systems allows rapid conversion from a closed to an open circuit during intraoperative emergencies, thereby minimizing safety concerns.

Vacuum-assisted venous drainage (VAVD) represents a critical component of many contemporary MIECC configurations, particularly in minimally invasive cardiac surgery where gravitational venous return may be insufficient. By applying controlled negative pressure to the venous drainage line, VAVD improves venous return, stabilizes circuit flow, and helps maintain adequate pump preload despite reduced circuit volume. However, excessive negative pressure may increase the risk of microbubble formation, hemolysis, or venous line collapse; therefore, careful pressure monitoring and standardized safety protocols are essential during clinical application (38). Although MIECC systems provide important

physiological and inflammatory advantages, they may not be suitable for all patient populations. Patients with severe ventricular dysfunction, massive venous return, or those requiring rapid volume administration may present challenges due to the limited reservoir capacity of closed-circuit configurations. In addition, complex multi-valve procedures, extensive aortic pathology, and cases with anticipated high cardiotomy suction demand may reduce the practicality of fully minimized circuits. Relative contraindications may also include centers with limited team experience in MIECC management, as inadequate familiarity with air management, vacuum-assisted venous drainage, and conversion strategies may increase intraoperative risk. Therefore, careful patient selection and institutional expertise remain essential factors when considering the use of MIECC technology.

Current Guidelines and Clinical Evidence for MIECC Use

Compared with CCPB and OPCABG procedures, MIECC demonstrates equivalent or superior outcomes in terms of mortality, blood loss, and transfusion requirements. Meta-analyses have shown that MIECC reduces the duration of intensive care unit and hospital stay, decreases perioperative blood loss, and lowers the incidence of arrhythmias. Furthermore, MIECC supports postoperative recovery by maintaining mean arterial pressure, preserving systemic vascular resistance, and ensuring adequate microcirculatory perfusion. When combined with minimally invasive cardiac surgery (MICS), MIECC offers a more physiological surgical approach by minimizing surgical trauma, preserving hematocrit levels, reducing postoperative bleeding, and lowering transfusion requirements. Additionally, its potential to reduce postoperative atrial fibrillation, protect renal function, and enhance myocardial protection has been reported (39).

Despite these benefits, MIECC may not be suitable for all patient populations. Patients with severe ventricular dysfunction, complex multi-valve procedures, extensive aortic pathology, or situations requiring rapid volume administration may present challenges when using a closed-circuit system. Centers with limited perfusion experience or insufficient training in MIECC management may also face increased intraoperative risks. Therefore, careful patient selection and team familiarity with the technology remain essential to ensure procedural safety.

Although MIECC systems provide important physiological advantages, economic considerations should also be acknowledged. In periods of increased healthcare resource constraints, the higher initial cost of minimized extracorporeal circuits compared with conventional cardiopulmonary bypass systems has been an important topic of discussion. Nevertheless, several centers have continued to adopt MIECC because of its reduced

inflammatory burden, lower transfusion requirements, and the potential to shorten ICU stay, factors that may partially offset the initial financial impact. Importantly, current evidence does not support the routine application of MIECC in all cardiac surgery procedures. Instead, a patient-tailored strategy appears more appropriate. MIECC may provide the greatest benefit in minimally invasive procedures, patients with low body surface area, or cases where blood conservation is essential, whereas conventional cardiopulmonary bypass may remain preferable in complex multivalve surgery, severe ventricular dysfunction, or situations requiring rapid volume management.

Therefore, a balanced cost–effectiveness evaluation and individualized patient selection are recommended rather than routine application in all cardiac surgery cases. Despite these advantages, the adoption of MIECC remains limited due to demanding training requirements, the necessity for thorough understanding of perfusion techniques, and the need for close intraoperative collaboration among the surgical team. MIECC is more commonly used in Europe, whereas its application in North America is less frequent, and the number of related studies remains limited. Recently, MIECC has been incorporated into the STS/SCA/AmSECT/SABM guidelines as a blood conservation strategy, with efforts to expand its use including the development of customized components and presentation of new case series in complex procedures (40).

CONCLUSION

MIECC systems represent advanced perfusion technologies developed to mitigate hemodynamic disturbances, systemic inflammatory response, and perioperative complications associated with CPB in cardiac surgery. Evidence from the literature indicates that MIECC preserves hematocrit, reduces transfusion requirements, and supports organ function through its closed-circuit design, reduced priming volume, heparin-coated biocompatible surfaces, and modular components.

Clinical studies and meta-analyses have demonstrated that the use of MIECC decreases postoperative morbidity, protects myocardial, renal, and cerebral functions, and significantly reduces inflammatory markers. Thanks to its closed-circuit configuration and optimized techniques, heparin requirements are lower, bleeding risk is minimized, and patient safety is enhanced. Various types and models of MIECC are compatible with MICS, providing intraoperative flexibility and rapid adaptation in emergency situations.

However, the safe and effective utilization of MIECC relies on the surgical and perfusion teams being prepared to manage potential complications and possessing sufficient knowledge and experience. Therefore, comprehensive team training and strengthening the capacity to

handle technical challenges are critical. To promote broader adoption, more teams should be encouraged to utilize the system, and robust clinical studies are needed to address system management, technical limitations, and problem-solving strategies.

In conclusion, MIECC systems provide a safe and effective perfusion approach, offering substantial clinical and physiological advantages in cardiac surgery. Future research will further clarify the role of MIECC technology in terms of long-term clinical outcomes, cost-effectiveness, and applicability across broader patient populations.

Scientific Responsibility Statement

The authors declare that they are responsible for the article's scientific content including study design, data collection, analysis and interpretation, writing, some of the main line, or all of the preparation and scientific review of the contents and approval of the final version of the article.

Ethics Approval and Consent

Ethical approval was not required since it was a review article.

Conflict of Interest

No conflict of interest was declared by the authors.

Author Contributions

Gülşah Celik Korhan: Article hypothesis, Literature review, Writing.

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