

Pump-controlled retrograde trial off in veno-arterial extracorporeal membrane oxygenation weaning: a scoping review of physiological rationale, protocol heterogeneity, and clinical application

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Abstract

Background Veno-arterial extracorporeal membrane oxygenation (V-A ECMO) is increasingly used for refractory cardiogenic shock; however, strategies to assess readiness for decannulation remain poorly defined. Although pump-controlled retrograde trial off (PCRTO) is a novel weaning assessment, its conceptual basis and clinical role remain unclear. This scoping review aimed to map the existing evidence on PCRTO in V-A ECMO, focusing on its methodological definition, implementation, monitoring strategies, and reported outcomes, and to identify key knowledge gaps.

Methods We conducted a scoping review following the established methodological guidelines and Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews checklist. Using the Patient–Concept–Context framework, we included studies involving neonatal, pediatric, and adult patients supported with V-A ECMO who underwent PCRTO. MEDLINE, Embase, CENTRAL, and ClinicalTrials.gov were searched from inception without language or date restrictions. Two reviewers (YI and HM) independently screened studies and extracted data using a standardized charting form, and the findings were descriptively summarized.

Results Twenty-one studies were included, predominantly case reports and case series, with limited observational data. PCRTO protocols substantially varied across studies, including differences in retrograde flow targets (commonly -0.5 to -1.0 L/min or -5 to -10 mL/kg/min), trial duration (minutes to several hours), and circuit management. Monitoring approaches were heterogeneous and frequently incorporated hemodynamic, metabolic, and echocardiographic parameters. Successful weaning was commonly reported; however, definitions of outcome and adverse events were inconsistent.

Conclusions PCRTO is a conceptually distinct weaning assessment in V-A ECMO that may provide additional physiological information beyond conventional flow reduction, particularly in evaluating right ventricular reserve.

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However, its definition, optimal protocol, and clinical effectiveness remain to be established. Further studies are required to standardize its physiological framework and clarify its role in V-A ECMO weaning.

Keywords Veno-arterial extracorporeal membrane oxygenation · Pump-controlled retrograde trial off · Scoping review · Preferred reporting items for systematic reviews and meta-analyses extension for scoping reviews checklist

Background

Veno-arterial extracorporeal membrane oxygenation (V-A ECMO) is used as a rescue therapy for severe circulatory failure [1]. In the United States, >15,000 patients with cardiogenic shock (CS) received V-A ECMO between 2002 and 2018, representing a 23-fold increase in use during this 16-year period [2]. Despite advances in patient selection and circuit management, the criteria and timing for decannulation remain poorly defined. Conventional assessment typically involves stepwise ECMO flow reduction to approximately 0.5–1.0 L/min, followed by the evaluation of echocardiographic parameters, such as velocity–time integral, left ventricular ejection fraction (LVEF), and other indices of biventricular function, in combination with hemodynamic stability, biochemical markers of tissue perfusion, and the level of vasoactive or inotropic support requirement, to determine readiness for decannulation [3]. However, the successful ECMO liberation rate, defined as survival after decannulation of ECMO without additional mechanical support, is approximately 30–50% [4–7]. Conventional low-flow weaning assessment may not fully reproduce the hemodynamic conditions present after ECMO decannulation, potentially limiting the evaluation of native cardiopulmonary reserve [6]. Therefore, alternative approaches that provide a more physiological assessment of native cardiopulmonary function may improve the evaluation of readiness for V-A ECMO decannulation.

Given the limitations of conventional weaning assessment, an alternative strategy for evaluating readiness for decannulation has been explored: pump-controlled retrograde trial off (PCRTO). PCRTO is a novel technique that involves reducing pump speed to allow controlled, retrograde blood flow through the ECMO circuit. Originally described in neonates to permit prolonged weaning trials while minimizing the risk of circuit thrombosis [8], this method has since been adapted for adults and is increasingly adopted as a routine assessment in some centers [3, 9, 10].

However, substantial heterogeneity exists in the methodology of PCRTO, and key aspects, including patient selection, optimal retrograde flow targets, trial duration, anticoagulation strategies, standardized hemodynamic and metabolic assessment, and possible complications, remain incompletely understood. To date, no comprehensive review has synthesized this evidence, and standardized operational definitions of PCRTO remain unavailable. This heterogeneity may limit the interpretation of existing studies and hinder the development of standardized weaning strategies.

Thus, this scoping review aimed to synthesize existing reports on PCRTO in V-A ECMO, outlining how it has been defined and implemented, the criteria guiding its use, the monitoring and evaluation methods used, and the outcomes and safety considerations reported to date.

Methods

Protocol and registration

The study protocol was registered on the Open Science Framework (doi:<https://doi.org/10.17605/OSF.IO/HZYXK>). This manuscript has been developed in accordance with the Preferred Reporting Items for Systematic reviews

and Meta-Analyses extension for scoping reviews (PRISMA-ScR) guidelines and the guidelines for a scoping review [11, 12].

Eligibility criteria

This scoping review was conducted based on the Patient–Concept–Context framework. Manuscripts included neonatal, pediatric, and adult patients supported with V-A ECMO who underwent PCRT. The concept of interest was the application of PCRT as a weaning strategy, including its protocol characteristics, physiological basis, safety, and clinical outcomes. Specific aspects included flow settings, duration, patient selection, monitoring strategies, and failure criteria. The context included any clinical setting where V-A ECMO was applied, such as intensive care units and operating rooms.

This review considered a broad range of evidence sources, including experimental and quasi-experimental studies (e.g., randomized controlled trials and nonrandomized studies), observational studies (e.g., cohort, case–control, and cross-sectional studies), and descriptive studies (e.g., case reports and case series). Qualitative studies and text and opinion papers were also included to comprehensively capture available evidence.

Conference abstracts were excluded because their limited reporting precluded sufficiently detailed data charting of PCRT methodology, monitoring strategies, and reported outcomes. No restrictions were otherwise applied regarding study design, as the aim of this scoping review was to comprehensively map the extent and characteristics of the available evidence.

Information sources and search strategy

A comprehensive search was conducted in MEDLINE (via PubMed), Embase (via Elsevier), Cochrane Central Register of Controlled Trials (CENTRAL), and ClinicalTrials.gov. In addition, the reference lists of the included studies and relevant reviews were screened to identify additional eligible studies.

A three-step search strategy was used. First, an initial limited search of MEDLINE, Embase, CENTRAL, and ClinicalTrials.gov was performed to identify relevant articles. The text words contained in the titles and abstracts of these articles and index terms used to describe them were used to develop a full search strategy for each database. The search strategy was adapted for each database, as appropriate, without language or date restrictions. The search was conducted up to October 4, 2025. The detailed search strategies for each database are provided in Additional file 1.

Selection of sources of evidence and data charting process

All identified records were collated and imported into Rayyan (Qatar Computing Research Institute, Doha, Qatar), and duplicates were removed. Titles and abstracts were independently screened by two reviewers based on the eligibility criteria. Potentially relevant articles were retrieved in full text and independently assessed by two reviewers (YI and HM). Any disagreements between reviewers were resolved through discussion or by consultation with a third reviewer. Reasons for exclusion at the full-text stage were recorded. The study selection process is presented using a PRISMA flow diagram. Data were independently extracted by two reviewers using a standardized data charting form developed in Microsoft Excel. The form was piloted on a sample of included studies and refined as required during data extraction. Any modifications to the data charting form were documented.

Data items

The following data were extracted: study characteristics (e.g., first author, year, country, study design, and population type), ECMO-related parameters (e.g., indication, circuit configuration, pre-PCRT flow, ECMO console or pump, oxygenator, and device-related technical considerations), detailed PCRT protocol characteristics

(e.g., retrograde flow targets, duration, sweep gas management, anticoagulation strategy including additional anticoagulation and coagulation monitoring, and adjunctive interventions), monitoring parameters, and reported outcomes (e.g., weaning success, decannulation failure, mortality, and complications). Study limitations and additional comments were also recorded. Given the heterogeneity of monitoring strategies, monitoring parameters were categorized into five domains to facilitate comparison across studies: hemodynamic monitoring (e.g., mean arterial pressure (MAP), heart rate (HR), central venous pressure, and vasoactive or inotropic support), echocardiographic assessment (e.g., LVEF, left ventricular outflow tract velocity–time integral (LVOT-VTI), and tricuspid annular plane systolic excursion (TAPSE)), metabolic and respiratory monitoring (e.g., lactate, arterial blood gas analysis, and oxygenation parameters), pulmonary artery catheter (PAC)-derived monitoring (e.g., pulmonary artery pressure, pulmonary capillary wedge pressure, cardiac index, and pulmonary artery pulsatility index (PAPi)), and tissue perfusion monitoring (e.g., near-infrared spectroscopy, central venous oxygen saturation and mixed venous oxygen saturation).

Synthesis of results

Extracted data were summarized in tabular and graphical formats to map the extent, range, and nature of the available evidence. Data were grouped according to key domains, including PCRTO definitions, protocol characteristics, monitoring strategies, and reported outcomes. Heterogeneity across studies was descriptively explored and narratively presented to highlight variations in PCRTO implementation and identify gaps in the current literature.

Results

Selection of sources of evidence

A comprehensive search identified 58 records from electronic databases. After removing 20 duplicates, 38 records were screened based on titles and abstracts, of which three were excluded because they were unrelated to PCRTO. Thirty-five reports were sought for retrieval and assessed for eligibility. Of these, 14 reports were excluded: 13 conference abstracts and one non-journal article. Finally, 21 studies were included in this scoping review. The study selection process is summarized in the PRISMA flow diagram (Fig. 1).

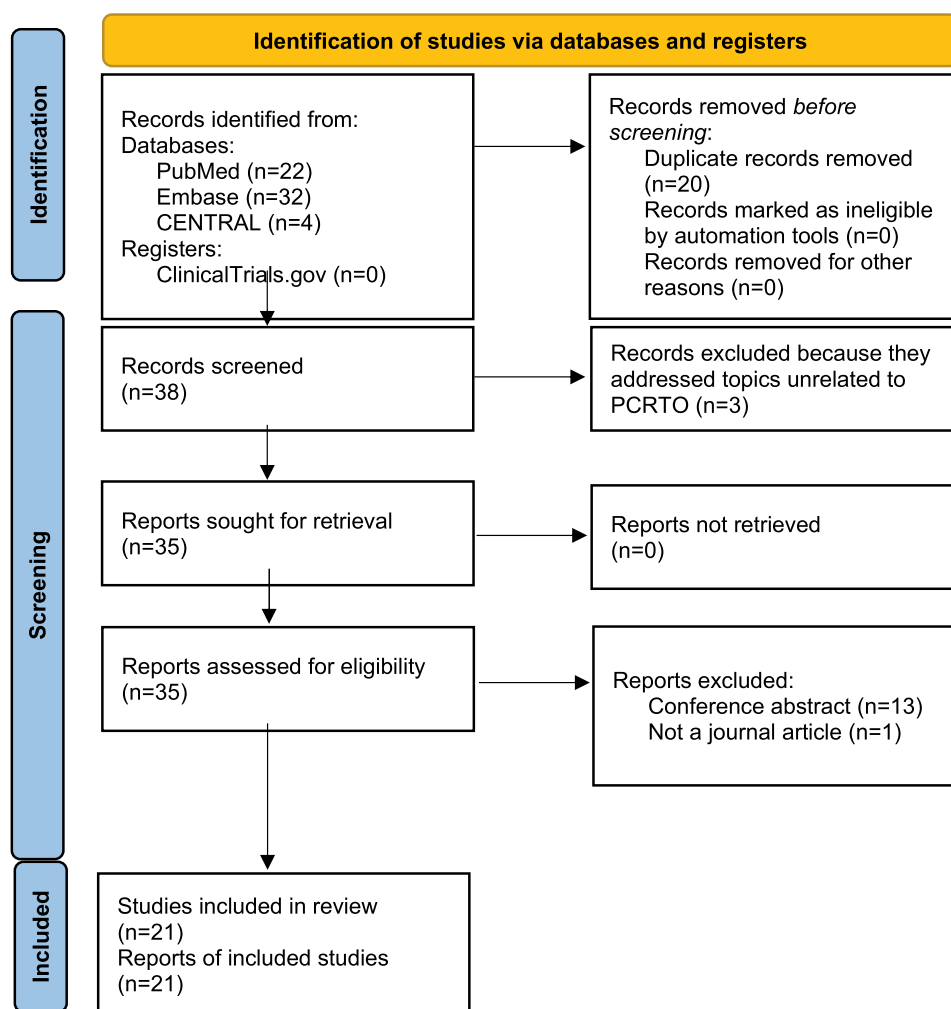
Characteristics of sources of evidence

Most included studies were case-based reports ($n=11$), including case reports and case series, whereas a smaller number of clinical studies ($n=6$), such as retrospective observational and cohort studies, were identified. A limited number of letters, commentaries, and non-original reports ($n=3$) and one systematic review were also included.

Most studies involved adult patients with V-A ECMO support ($n=14$), although pediatric and neonatal populations were also represented ($n=5$). Sample sizes substantially varied, ranging from single-patient case reports to larger cohort studies.

The clinical indications for V-A ECMO were heterogeneous across included studies, with CS the most commonly reported. The predominant underlying etiologies were ischemic heart disease, myocarditis, and post-cardiotomy cardiac dysfunction. Extracorporeal cardiopulmonary resuscitation accounted for a substantial proportion in several cohorts. Pulmonary embolism was a rare indication, reported only in isolated case reports. The key characteristics of the included studies are summarized in Table 1. Larger clinical series were predominantly reported from Korea, China, Australia, and the United Kingdom, whereas reports from Japan, India, Singapore, and Canada were mainly limited to isolated case reports, small case series, or conceptual reports.

Fig. 1 PRISMA flow diagram of the study selection process. The diagram illustrates the identification, screening, and inclusion of studies for this scoping review. From the initial 58 records identified through database searches, 21 studies were ultimately included in the final synthesis. PRISMA, Preferred reporting Items for systematic reviews and meta-Analyses



Clinical application of pump-controlled retrograde trial off (PCRT0)

Definition

Nineteen of the 21 included studies provided at least a conceptual or procedural description of PCRT0. Most commonly, PCRT0 was described as a temporary reduction of ECMO pump speed to allow a controlled, retrograde blood flow through the arterial cannula. In contrast, two studies did not provide a sufficiently detailed procedural definition: one case report stated that PCRT0 was performed without clearly describing the flow setting or implementation method [18], and one systematic review discussed PCRT0 only as a weaning strategy rather than as a defined protocol [3].

Key methodology for PCRT0

Table 2 summarizes the key findings of the PCRT0 methodology. Retrograde flow targets were reported in 17 of 21 studies and, where described, were based on either fixed flow settings or body weight-adjusted targets. Fixed retrograde flow targets ranged from 0.5 to 1.0 L/min in adult studies and from 100 to 250 mL/min in pediatric studies, whereas weight-based strategies typically targeted 5–10 mL/kg/min. However, the rationale for selecting these targets was often not explicitly described. In 14 of 21 studies, sweep gas was turned off during PCRT0 to assess native pulmonary function. In one case report, sweep gas was maintained during V-AV ECMO weaning,

Table 1 Key characteristics of included studies

Author	Year	Country	Study design	Configuration	Population	N	ECMO indication
Deshpande et al. [13]	2025	India	Case report	V-A	Adult	1	Cardiogenic shock
Matsumura et al. [14]	2025	Japan	Case report	V-AV	Adult	1	Septic cardiomyopathy
Fiorelli et al. [15]	2025	UK	Multicenter pilot study	V-A	Adult	21	Cardiogenic shock
Menon et al. [16]	2025	Singapore	Case series	V-A	Neonatal/Pediatric	2	Cardiac arrest by ARDS Neonatal myocarditis
Jo et al. [10]	2024	Korea	Retrospective study	V-A	Adult	155	Cardiac arrest, Cardio- genic shock
Zhang et al. [17]	2024	China	Case report	V-A	Adult	1	Pulmonary embolism
Bian et al. [18]	2024	China	Case report	V-A	Adult	1	Cardiac arrest
Lau et al. [9]	2023	Hong Kong	Case series	V-A	Adult	36	Mixed cardiogenic causes
Xu et al. [19]	2023	China	Retrospective study	V-A	Adult	20	Cardiac arrest, Cardiogenic shock
Charbonneau et al. [3]	2022	Canada	Systematic review	NA	Adult	NA	NA
Serri et al. [20]	2022	Canada	Letter	NA	NA	NA	Not specified
Matsumura et al. [21]	2022	Japan	Case report	V-A	Adult	1	Pulmonary embolism
Ju et al. [22]	2021	Korea	Retrospective study	V-A	Adult	47	Cardiogenic shock
Lijuan Jia et al. [23]	2020	China	Retrospective cohort study	V-A	Adult	21	Cardiac arrest, Cardiogenic shock
Xu et al. [24]	2019	China	Case report	V-A	Adult	1	Myocarditis
Pandya et al. [25]	2019	Australia	Retrospective study	V-A	Pediatric	51	Mixed indications
Mattke et al. [26]	2019	Australia	Letter	NA	NA	NA	NA
Mattke et al. [27]	2019	Australia	Letter	NA	Pediatric	NA	NA
Ling et al. [28]	2018	China	Case series	V-A	Adult	7	Cardiogenic shock
Mattke et al. [29]	2017	Australia	Case series	V-A	Neonatal/Pediatric	17	Mixed indications
Westrope et al. [8]	2013	UK	Case series	V-A	Neonatal	5	Respiratory causes

ECMO, extracorporeal membrane oxygenation; V-A, veno-arterial; V-AV, veno-arteriovenous

likely reflecting the need to preserve adequate gas exchange [14]. The management of the distal perfusion cannula (DPC) varied across studies. In five studies, the DPC was clamped or disconnected, and in three of those it was also flushed with heparinized saline, whereas DPC management was not specifically described in the remaining studies. The duration of PCRT0 substantially varied. Across studies, 30–60 min was the most commonly reported duration (11 studies); however, shorter (<30 min, two studies) and longer (61–120 min, six studies) durations were also described, and some protocols extended PCRT0 up to 8 h in borderline cases [10]. Several studies also adopted flexible, response-guided approaches based on hemodynamic stability and end-organ perfusion.

Table 3 summarizes the ECMO systems and device-related technical considerations reported during PCRT0. ECMO console, pump, or system information was reported in 11 of 21 studies, whereas the oxygenator was specified in eight studies. The systems included Rotaflow, Cardiohelp, Deltastream, CAPIOX, Bio-Console 560, Sorin system, and Thoratec Pedi-VAS. Technical approaches to measuring and maintaining retrograde flow varied across reports. Some studies described simple reversal of the flow-probe or flow/bubble-sensor direction, whereas others relied on external flow monitoring when integrated probes could not reliably measure low or retrograde flow. For Cardiohelp specifically, approaches ranged from probe- or sensor-direction reversal to temporary activation of “Global Override” with transfer of the flow probe [9, 20, 28]. Automatic backflow prevention was also reported as a potential cause of unintended PCRT0 termination [26]. In one neonatal case, PCRT0 was terminated after 5 min because the achieved retrograde flow remained substantially below the manufacturer-recommended minimum oxygenator flow, illustrating how minimum flow requirements may limit PCRT0 feasibility in small patients [16].

Table 4 summarizes anticoagulation management during PCRT0. Anticoagulation was generally maintained according to standard ECMO protocols. In seven reports, additional heparin boluses were administered before or

Table 2 Key characteristics of PCRTO methodology

Study	Retrograde flow target (absolute value)	Flow setting basis	Duration of PCRTO	Sweep gas off	DPC management
Deshpande et al. 2025 [13]	0.5–1.0 L/min	Not described	40 min	Yes	Not described
Matsumura et al. 2025 [14]	0.7 L/min	10 mL/kg/min	2 h	Maintained	Not described
Fiorelli et al. 2025 [15]	0.5–1.0 L/min	Not described	30 min	Yes	Clamped and flushed
Menon et al. 2025 [16]	0.17 L/min/0.04 L/min	10 mL/kg/min	45 min/5 min	Yes	Not described
Jo et al. 2024 [10]	300–800 mL/min	5–10 mL/kg/min	60–120 min, up to 8 hours	Yes	Not described
Zhang et al. 2024 [17]	0.5 L/min	Not described	Not described	Not described	Not described
Bian et al. 2024 [18]	Not specified	Not described	Not described	Not described	Not described
Lau et al. 2023 [9]	0.5–1.0 L/min	10 mL/kg/min	120–240 min	Yes	Clamped and flushed
Xu et al. 2023 [19]	0.5–1.0 L/min	Not described	30 min	Yes	Clamped
Charbonneau et al. 2022 [3]	0.5–1.0 L/min	Not described	Not described	Yes	Not described
Serri et al. 2022 [20]	NA	NA	Not described	Not described	Not described
Matsumura et al. 2022 [21]	0.83–0.98 L/min	Not described	1 h	Yes	Not described
Ju et al. 2021 [22]	300 to 800 mL/min	10 mL/kg/min	30 min–4 h	Not described	Not described
Lijuan Jia et al. 2020 [23]	500 to 600 mL/min	Not described	1 h	Yes	Not described
Xu et al. 2019 [24]	0.5–1.0 L/min	Not described	1 h	Yes	Not described
Pandya et al. 2019 [25]	100 to 250 mL/min	Body weight basis	Median 88 min	Yes	Clamped and flushed
Mattke et al. 2019 [26]	NA	NA	NA	Not discussed	Not described
Mattke et al. 2019 [27]	NA	NA	NA	Not discussed	Not described
Ling et al. 2018 [28]	0.5–1.0 L/min	Not described	1 h	Yes	Clamped
Mattke et al. 2017 [29]	100–250 mL/min	Not described	15 min–2.5 h	Yes	Not described
Westrope et al. 2013 [8]	120 mL/min	Not described	2–5 h	Yes	Not described

PCRTO, pump-controlled retrograde trial off; DPC, distal perfusion cannula

during PCRTO to mitigate the risk of circuit thrombosis. Monitoring strategies varied across studies: activated clotting time was reported in eight studies, activated partial thromboplastin time in five studies, and anti-factor Xa monitoring in two studies. One study also described routine inspection of the ECMO circuit before and after PCRTO to detect thrombus or fibrin formation as an additional procedural safety measure before flow reversal [15]. Technical challenges related to ECMO console operation during PCRTO were described in a limited number of reports. Mattke et al. highlighted that some ECMO consoles incorporated automatic retrograde flow prevention software, which might inadvertently terminate PCRTO and lead to inaccurate assessment of readiness for decannulation or blood stasis within the circuit [26]. To address these challenges, Serri et al. described practical operational strategies, including temporarily overriding flow regulation alarms and repositioning the flow probe to facilitate retrograde flow [20].

Table 3 ECMO systems and device-related technical considerations during PCRTO

Study	ECMO system	Technical requirements/issues
Deshpande et al. 2025 [13]	Rotaflow console; oxygenator not reported	Negative console flow reading; visual confirmation from blood color
Matsumura et al. 2025 [14]	Cardiohelp console; HLS oxygenator	V-AV ECMO: removal of femoral venous return-line occluder
Fiorelli et al. 2025 [15]	Not reported	Not reported
Menon et al. 2025 [16]	Deltastream console; Medos Hilite 2400 oxygenator	Flow-probe reversal; PCRTO stopped because flow remained below the manufacturer-recommended minimum oxygenator flow
Jo et al. 2024 [10]	Not reported	Not reported
Zhang et al. 2024 [17]	Not reported	Not reported
Bian et al. 2024 [18]	Not reported	Not reported
Lau et al. 2023 [9]	Cardiohelp or Rotaflow console; HLS or PLS oxygenator	Cardiohelp: flow/bubble-sensor reversal; alarm adjustment
Xu et al. 2023 [19]	Not reported	Negative console flow reading
Charbonneau et al. 2022 [3]	Not reported	Not reported
Serri et al. 2022 [20]	Not reported	Temporary Global Override; flow-probe transfer to venous line; bubble-detection reset/unlinking
Matsumura et al. 2022 [21]	CAPIOX Emergency Bypass System with CAPIOX Centrifugal Pump SL and CAPIOX LX oxygenator	Not reported
Ju et al. 2021 [22]	PLS or EBS system; components not separately reported	Arterial flow-probe reversal in EBS system
Jia et al. 2020 [23]	Bio-Console 560, Sorin system, or Rotaflow console; oxygenator not reported	Negative console flow reading
Xu and Gu 2019 [24]	Not reported	Arterial flow-probe reversal
Pandya et al. 2019 [25]	Rotaflow console; Quadrox-iD pediatric oxygenator	External Transonic flow probe for low-flow measurement
Mattke et al. 2019 [26]	Not reported	Cardiohelp: automatic backflow prevention/zero-flow mode; Global Override disabled other automated safety features
Mattke et al. 2019 [27]	Not reported	Not reported
Ling and Chan 2018 [28]	Cardiohelp console; HLS oxygenator	Arterial flow-probe reversal
Mattke et al. 2017 [29]	Rotaflow console; Quadrox-iD pediatric oxygenator	External Transonic flow probe for low/retrograde-flow measurement
Westrope et al. 2013 [8]	Thoratec Pedi-VAS centrifugal pump; Medos Hilite 800 LT oxygenator	Flow-probe reversal

ECMO, extracorporeal membrane oxygenation; PCRTO, pump-controlled retrograde trial off; V-AV, veno-arteriovenous; PLS, Permanent Life Support; EBS, Emergency Bypass System; HLS, Heart-Lung Support

Patient selection

In clinical studies, PCRTO was performed in patients considered ready for weaning from V-A ECMO, most commonly defined by evidence of cardiac recovery, hemodynamic stability, and adequate end-organ perfusion. For example, one multicenter study required lactate level < 2 mmol/L, MAP > 60 mmHg, and improving echocardiographic parameters, such as LVOT-VTI before performing PCRTO [15]. Case reports and series described right ventricular dilatation, increased tricuspid regurgitation, and right ventricular failure during PCRTO, whereas other studies incorporated right heart-focused monitoring, including echocardiographic indices, such as TAPSE and PAC-derived parameters [15, 17, 19, 24, 28]. These findings suggest that right ventricular function may influence the hemodynamic response and may be relevant to patient selection.

Conversely, certain conditions were identified as potential contraindications. Notably, the presence of a significant intracardiac shunt (e.g., patent foramen ovale) was explicitly described as a contraindication in two studies

Table 4 Anticoagulation strategy during PCRTO

Study	Additional anticoagulation during PCRTO	Target/monitoring
Deshpande et al. 2025 [13]	Not described	ACT 180–200 s
Matsumura et al. 2025 [14]	Not described	aPTT ~60 s
Fiorelli et al. 2025 [15]	Not described	anti-Xa > 0.3 IU/mL
Menon et al. 2025 [16]	Heparin bolus	ACT 200–250 s, aPTT 70–100 s
Jo et al. 2024 [10]	Heparin bolus	ACT 200–220 s/aPTT 40–60 s
Zhang et al. 2024 [17]	Not described	Not specified
Bian et al. 2024 [18]	Not described	Not described
Lau et al. 2023 [9]	Not described	APTT 1.5–2.5×
Xu et al. 2023 [19]	Heparin bolus	ACT 200–250 s
Charbonneau et al. 2022 [3]	Not described	Not described
Serri et al. 2022 [20]	Not described	Not described
Matsumura et al. 2022 [21]	Heparin bolus	Not specified
Ju et al. 2021 [22]	Not described	aPTT > 70 s
Lijuan Jia et al. 2020 [23]	Heparin bolus	ACT 200–300 s
Xu et al. 2019 [24]	Heparin bolus	ACT > 220 s
Pandya et al. 2019 [25]	Not described	Standard ECMO anticoagulation
Mattke et al. 2019 [26]	Not described	Not described
Mattke et al. 2019 [27]	Not described	Not described
Ling et al. 2018 [28]	Heparin bolus	ACT 220–250 s
Mattke et al. 2017 [29]	Not described	Anti-Xa ≥ 0.5
Westrope et al. 2013 [8]	Not described	ACT 200–220 s

ACT, activated clotting time; aPTT, activated partial thromboplastin time; ECMO, extracorporeal membrane oxygenation

[15, 20]. In addition, some studies suggested that PCRTO should be avoided or used cautiously in patients with severe respiratory failure or poor native lung function, where turning off sweep gas may lead to inadequate gas exchange [9]. Overall, patient selection criteria were heterogeneous and often not explicitly defined, and no standardized indications for PCRTO were identified in the literature.

Monitoring and assessment

Monitoring strategies during PCRTO are summarized in Table 5. Monitoring parameters were categorized into five domains: hemodynamic, echocardiographic, metabolic and respiratory, PAC-derived, and tissue perfusion monitoring. Hemodynamic monitoring was reported in 17 of 21 studies (81.0%) and typically included MAP, HR, blood pressure, and vasoactive or inotropic support requirements. Echocardiographic assessment was described in 13 of 21 studies (61.9%) and commonly included LVOT-VTI, LVEF, and right ventricular functional indices, such as TAPSE. Metabolic and respiratory monitoring was reported in 16 of 21 studies (76.2%), primarily through serum lactate measurement and arterial blood gas analysis. In contrast, PAC-derived monitoring was documented in six of 21 studies (28.6%) and tissue perfusion monitoring in three of 21 studies (14.3%). No standardized monitoring protocol for PCRTO was identified, and considerable heterogeneity in monitoring approaches was observed across studies.

Outcomes and adverse events

Outcomes and adverse events, associated with PCRTO, were heterogeneously reported across studies.

In clinical studies, outcomes were more systematically reported and primarily focused on successful weaning from V-A ECMO, survival to hospital discharge, and physiological responses during PCRTO. Reported successful weaning rates appeared relatively high among patients who underwent PCRTO; however, interpretation is limited by the predominance of case-based reports, selected retrospective cohorts, and the pre-selection of

Table 5 Hemodynamic monitoring strategy during PCRT0

Study	Hemodynamics	Echocardiography	Metabolic/respiratory	PAC-derived	Tissue perfusion
Deshpande et al. 2025 [13]	✓	✓	✓	✓	
Matsumura et al. 2025 [14]	✓	✓	✓		
Fiorelli et al. 2025 [15]	✓	✓	✓	✓	
Menon et al. 2025 [16]	✓	✓	✓		
Jo et al. 2024 [10]	✓		✓		
Zhang et al. 2024 [17]	✓	✓		✓	
Bian et al. 2024 [18]					
Lau et al. 2023 [9]	✓	✓	✓		✓
Xu et al. 2023 [19]	✓	✓	✓	✓	✓
Charbonneau et al. 2022 [3]	✓		✓		
Serri et al. 2022 [20]					
Matsumura et al. 2022 [21]	✓	✓	✓	✓	
Ju et al. 2021 [22]	✓	✓	✓		
Lijuan Jia et al. 2020 [23]	✓	✓	✓		✓
Xu et al. 2019 [24]	✓	✓	✓	✓	
Pandya et al. 2019 [25]	✓	✓	✓		
Mattke et al. 2019 [26]					
Mattke et al. 2019 [27]					
Ling et al. 2018 [28]	✓	✓	✓		
Mattke et al. 2017 [29]	✓		✓		
Westrope et al. 2013 [8]	✓		✓		

PAC, pulmonary arterial catheter
 ✓, monitoring parameter explicitly described in the methods or results of the source; blank, parameter not reported (absence of reporting does not necessarily indicate that monitoring was not performed)

patients deemed sufficiently stable to undergo PCRTO. For example, Lau et al. included 36 patients who underwent PCRTO. Of the 35 patients with at least one successful PCRTO session, 31 (88.6%) were subsequently weaned from ECMO; one additional patient underwent decannulation despite not completing a successful session [9], whereas Xu et al. and Lijuan Jia et al. reported success rates of 65% and 69.2%, respectively [19, 23]. In particular, Jo et al. demonstrated a higher survival to discharge rate in the PCRTO group compared with conventional weaning [10]. Importantly, Fiorelli et al. reported discordant results between PCRTO and conventional weaning in 13 of 32 trials, suggesting that PCRTO may provide additional physiological information that influences clinical decision-making [15].

In contrast, case reports and series primarily described individual patient trajectories and procedural feasibility. Although most reports described successful ECMO weaning following PCRTO, the unsuccessful or interrupted PCRTO was often associated with right ventricular dysfunction or transient hemodynamic instability, indicating that PCRTO may unmask instability not apparent under conventional V-A ECMO weaning [17].

Adverse events were infrequently reported across studies. When described, complications included transient hemodynamic instability, right ventricular failure, reduced tissue perfusion, and neurological events, such as seizures [9]. Thrombotic complications were rare, with only isolated cases reported, such as distal perfusion catheter thrombosis [15].

Discussion

PCRTO more comprehensively assesses residual native cardiac function under altered loading conditions during V-A ECMO weaning. This scoping review demonstrated substantial heterogeneity in the definition, implementation, and reported outcomes across the literature, highlighting that it remains a weaning strategy that is sporadically and inconsistently adopted across ECMO centers. Although PCRTO was originally introduced in neonatal practice to facilitate prolonged weaning assessment without circuit clamping, its application has since expanded to adult populations with varying procedural approaches. Overall, the current evidence base remains limited and largely based on case reports, with inconsistent descriptions of protocol elements and assessment criteria.

A key finding of this scoping review is the substantial heterogeneity in PCRTO protocols, including trial duration, sweep gas management, circuit handling, and monitoring strategies, whereas retrograde flow targets were relatively consistent within adult and pediatric populations. This variability reflects multiple underlying factors, including limited evidence, differences in patient populations (adult vs. pediatric), and, importantly, the limited physiological and mechanistic evidence underpinning PCRTO implementation. In this context, heterogeneity should not be interpreted only as inconsistency in practice but also as a reflection of the evolving and incompletely defined role of PCRTO in ECMO weaning.

PCRTO differs from conventional V-A ECMO flow reduction in the magnitude and change in loading conditions to the left and right ventricles. Conventional flow reduction decreases extracorporeal support and may increase native pulmonary circulation, but does not actively augment venous return to the same extent [30]. In addition, this low-flow strategy is still associated with reduced right ventricular preload [28], potentially limiting adequate assessment of right heart function. In contrast, by allowing retrograde flow from the arterial to the venous system, PCRTO increases venous return and augments pulmonary blood flow, thereby increasing right ventricular preload and potentially altering loading conditions. Therefore, PCRTO may serve as a dynamic test of underlying right ventricular reserve: in patients with preserved right ventricular function, this perturbation may be well tolerated, whereas in those with impaired right ventricular and/or lung function, it may unmask latent instability [15, 19]. Additionally, PCRTO may influence systemic perfusion by creating a controlled arteriovenous shunt, potentially requiring compensatory increases in native cardiac output to maintain effective systemic circulation, as suggested in a prior conceptual study [27]. This raises the possibility that PCRTO may function as a broader cardiopulmonary–circulatory stress test and that the physiological response may differ depending on the underlying pattern of ventricular dysfunction. Because PCRTO uses the existing ECMO circuit, full

extracorporeal support can also be rapidly restored if the trial is not tolerated. Importantly, this mechanistic interpretation remains speculative and requires validation in dedicated studies, but it provides a plausible framework for explaining the observed clinical variability.

Given the complex physiological responses induced by PCRTO, the optimal monitoring strategy remains unclear. This likely reflects the absence of parameters that can adequately capture the underlying cardiopulmonary interactions. In particular, PCRTO may simultaneously affect right ventricular loading conditions and effective systemic perfusion, suggesting that both domains require assessment. However, the relative value of different monitoring modalities during PCRTO has not been systematically reported. Although PAC monitoring may provide detailed hemodynamic information, PAC-derived monitoring was reported in fewer than one-third of the included studies. This suggests that invasive hemodynamic assessment is currently used selectively during PCRTO rather than being routinely incorporated into weaning assessment. Whether broader adoption would improve physiological assessment or clinical decision-making during PCRTO remains unknown, and protocolized use during ECMO weaning has not been established. Echocardiographic assessment is widely used in conventional ECMO weaning [31–33]; however, its role in interpreting responses, particularly of right ventricular function, during PCRTO has not been specifically validated. Similarly, uncertainty persists regarding whether right ventricular–pulmonary circulation coupling, PAPI [34], metabolic markers such as lactate, or simple changes in vital signs provide the most reliable indicators of intolerance. Although a multimodal approach appears clinically reasonable, no standardized monitoring framework or validated failure criteria for PCRTO have been established.

In terms of clinical application, current evidence remains insufficient to support the routine use of PCRTO as either a replacement for or a routine complement to conventional weaning strategies, primarily owing to the limited quality of available evidence, uncertain indicating criteria, inconsistent outcome reporting, and substantial variability in PCRTO protocols. Most included studies consisted of case reports and series, with only a small number of observational clinical studies, and definitions of successful weaning and adverse event reporting considerably varied. In addition, key methodological elements—including ECMO flow targets, trial duration, and monitoring strategies—widely differed across studies. Device-related differences may further affect the feasibility and safety of PCRTO. In particular, console-specific flow-sensing and automatic backflow-prevention functions may require modification of the flow-probe configuration or alarm settings, or a software override. In addition, minimum oxygenator flow requirements may limit the achievable duration of PCRTO, especially in small patients. Although this heterogeneity may reflect real-world practice, it limits the ability to identify optimal procedural parameters, compare findings across studies, and synthesize results. The theoretical risks of systemic embolism of clots in the circuit also remain to be examined. Taken together, detailed preclinical studies and standardization of protocols are required to inform the design of prospective or randomized trials, so that the role of PCRTO in ECMO weaning can be better understood.

Limitations

This study has some limitations. As a scoping review, it provides a descriptive synthesis and does not allow for quantitative comparison or assessment of effect size. In addition, the prevalence and adoption of PCRTO across institutions could not be determined from the available literature, as most included studies were single-center or case-based reports. As such, the generalizability of these findings to routine ECMO practice remains unclear. Furthermore, given the predominance of case-based literature, publication bias is likely, as successful or favorable experiences are more likely to be reported and patients selected for PCRTO may already represent a preselected population, potentially leading to an overestimation of its feasibility or clinical effectiveness. Finally, although we systematically assessed ECMO systems and oxygenators, device information was inconsistently reported across the included studies. This limited our ability to determine how device-related differences may have influenced the feasibility and safety of PCRTO.

Conclusion

PCRTO is an emerging technique for evaluating readiness for weaning in patients receiving V-A ECMO. Current evidence suggests it may provide additional physiological information beyond conventional weaning strategies, particularly regarding right ventricular function. However, its conceptual basis, optimal implementation, and clinical role remain incompletely defined. Further studies are required to clarify its physiological mechanisms, standardize protocols, and determine its clinical utility relative to established weaning approaches.

Abbreviations

PRISMA-ScR	Preferred reporting items for systematic reviews and meta-analyses extension for scoping reviews
V-A ECMO	Veno-arterial extracorporeal membrane oxygenation
PCRTO	Pump-controlled retrograde trial off
CENTRAL	Cochrane central register of controlled trials
MAP	Mean arterial pressure
HR	Heart rate
LVEF	Left ventricular ejection fraction
LVOT-VTI	Left ventricular outflow tract velocity–time integral
TAPSE	Tricuspid annular plane systolic excursion
PAC	Pulmonary artery catheter
PAPi	Pulmonary artery pulsatility index
DPC	Distal perfusion cannula

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Data availability No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests John F. Fraser serves on the Advisory Board of Critical Care. Adrian C. Mattke, Brian Fung Ming LAU, Tammy Sin Kwan MA, Pauline Yeung NG, Francesca Fiorelli, Christophe Vandenbriele, Brijesh V Patel, and John F. Fraser authored studies included in this review. Study selection and data extraction were conducted independently by Yudai Iwasaki and Haruka Matsumoto, who were not authors of any included studies. The authors declare no other competing

interests.

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