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Experience in applied veno-arterial extracorporeal membrane oxygenation to support catheter ablation of malignant ventricular tachycardia

Shanfeng Zhang [a], Yueh-ting Chou [a,b], Jinlin Zhang [a], Jin Chen [a], Yiming Xiong [a], Juan Lu [a], Chao Chen [a], Yue Xu [a], Yan Liu [a,*]

[a] Wuhan Asia Heart Hospital, Wuhan, China
[b] National Taipei University of Nursing and Health Sciences, Taipei, Taiwan

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ABSTRACT

Background: An electrical storm due to malignant ventricular tachycardia (VT) is a life-threatening condition that requires catheter ablation (CA). Most VT arrhythmias evolve over time after acute myocardial infarction, coronary artery bypass grafting, or chronic heart failure. Clinically, only radiofrequency ablation can identify and block all arrhythmia origin points. The procedure necessitates continuous VT induction in patients, resulting in hemodynamic instability; therefore, extracorporeal membrane oxygenation (ECMO) support is required. Earlier studies have reported substantial mortality rates; however, our results are significantly more favorable. In this study, we combined the minimally invasive extracorporeal circulation (MiECC) approach with ECMO to preserve an appropriate ECMO flow rate, thus reducing intraoperative left heart afterload. We report 21 cases illustrating the usefulness of modified veno-arterial (VA)-ECMO in this scenario.

Methods: Data of 21 patients supported by the modified VA-ECMO system (MiECC approach combined with the ECMO system) during VT CA in the Wuhan Asia Heart Hospital between June 2020 and July 2021 were reviewed retrospectively.

Results: Successful ablation was achieved in 20 out of 21 patients (95%). The median time for ECMO implantation was 206 min. Only two patients experienced complications post-treatment. All patients made complete recovery and were discharged. All patients were alive at the 1-year-follow-up.

Conclusions: Our modified VA-ECMO system helped restore systemic circulation in patients experiencing an electrical storm, thus achieving greater electrical stability during VT CA. Pre-insertion of VA-ECMO can achieve even better results.

1. Introduction

Patients with ventricular tachycardia (VT) are at risk of acute hemodynamic decompensation and multiorgan failure [1]. Catheter ablation (CA) is an effective treatment [2,3], but the risk of hemodynamic instability due to recurrent VT, or electrical storm during mapping is high [4,5]. One study showed that 11 % of the 193 patients who underwent VT CA developed acute hemodynamic instability and had a long-term mortality rate of approximately 50 % [6].

Different hemodynamic support devices have been used in this interventional procedure [4,7,8], showing low efficacy [9]. For instance, one study found no significant difference in the 3-month mortality rate of a group with an intra-aortic balloon pump (IABP)-assisted radiofrequency ablation compared to that of a normal group (33 % vs. 41 %, respectively) [10]. Moreover, a retrospective study (n = 345) reported a mortality rate of 6.5 % and 19.1 % for percutaneous ventricular assist device (PVAD)-assisted radiofrequency ablation and IABP-assisted radiofrequency ablation, respectively; furthermore, they reported a 27 % mortality rate on patients with 30-day readmissions [11]. Additionally, the effectiveness of the Tandem Heart and the left ventricular assist device (LVAD; Impella 2.5, ABIOMED, Inc, Danvers, MA, USA) regarding CA was evaluated. For the pre-emptive and rescue use of

Abbreviations: VT, ventricular tachycardia; CA, catheter ablation; ECMO, extracorporeal membrane oxygenation; IABP, intra-aortic balloon pump; PVAD, percutaneous ventricular assist device; LVAD, left ventricular assist device; cECC, conventional extracorporeal circulation; MiECC, minimally invasive extracorporeal circulation; ICD, implantable cardioverter defibrillator; EF, ejection fraction; CPB, cardiopulmonary bypass; ACT, activated clotting time; CCU, coronary care unit.

* Corresponding author.
E-mail address: whyxyyly@aliyun.com (Y. Liu).

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LVAD adjuncts, overall 30-day mortality rates of 4.2 % and 58.3 % and long-term mortality rates of 74 % and 60 % were reported, respectively [12]. Similarly, a prospective, open, nonrandomized study (n = 20) showed a 30-day mortality rate of 10 % and a readmission rate of 25 % in patients with LVAD [13].

Veno-arterial extracorporeal membrane oxygenation (VA-ECMO) has been used to support radiofrequency ablation, reporting different outcomes [4,5]. A single-center retrospective study (n = 64) reported an in-hospital mortality rate of 1.5 % in patients receiving ECMO [1], while another study (n = 21) reported a rate of up to 62 % [14]. Additionally, postoperative complications often occur in patients assisted by ECMO [15], such as acute kidney failure, cardiogenic shock, vascular injury, acute heart failure, and thrombosis [1,16]. Therefore, research on the systemic inflammatory response, coagulopathy, gas or particle embolism, and central nervous system injury induced by conventional extracorporeal circulation (cECC) has increased [17]. Moreover, several studies have demonstrated that blood dilution, blood-to-blood contact, foreign-body contact reaction, and intracardiac pull in the cECC process can activate the systemic inflammatory response that might lead to the destruction of blood components, causing abnormalities in coagulation that may provoke myocardial injury, neurocognitive impairment, multiple organ failure, and even death [18]. To avoid the shortcomings of cECC and reduce the occurrence of cECC-related complications, Fromes et al. proposed minimally invasive extracorporeal circulation (MiECC) in 2002, an innovative approach in cardiopulmonary bypass technology [19]. MiECC possesses a small prefilling volume, which aims to reduce hemodilution and the consequent need for perioperative blood transfusion. Moreover, it uses a closed extracorporeal circulation pipeline where the patient acts as a venous reflux chamber. Importantly, MiECC is designed primarily for cardiac surgery that does not involve opening the atrium, such as coronary artery bypass grafting and aortic valve replacement [20–24].

The most commonly used mechanical circulatory support device in CA is ECMO [4,5], but its mortality rate is highly variable, and postoperative heart failure is often observed. Therefore, in this study, we combined the MiECC approach with ECMO to preserve an appropriate ECMO flow rate, thus reducing intraoperative left heart afterload.

2. Methods

The clinical data of 21 patients supported by VA-ECMO during VT CA in Wuhan Asia Heart Hospital between June 2020 and July 2021 was collected. A total of 412 patients were treated with VT CA during this period, and approximately 5 % (n = 21) of the patients underwent preventive VA-ECMO. This study was conducted and approved in accordance with the tenets of the Declaration of Helsinki and the Ethics Committee of the Wuhan Asia Heart Hospital (No.2022-B003). Informed consent was obtained from all the participants involved in the study.

One patient with dilated cardiomyopathy and several comorbidities (hypertension, coronary disease, diabetes, and renal failure) presented with VT during the CA mapping process, and VA-ECMO treatment was needed after electrical defibrillation failed. Thus, we pre-emptively applied VA-ECMO during VT CA in patients with a poor condition and multi-organ comorbidities [7], such as liver and kidney insufficiency, hypertension, and cerebral infarction. In addition, patients undergoing ECMO-assisted ablation of organic VT, who developed hemodynamic instability during clinical episodes of VT, were enrolled. All patients received preoperative medication and had a poor outcome, and some

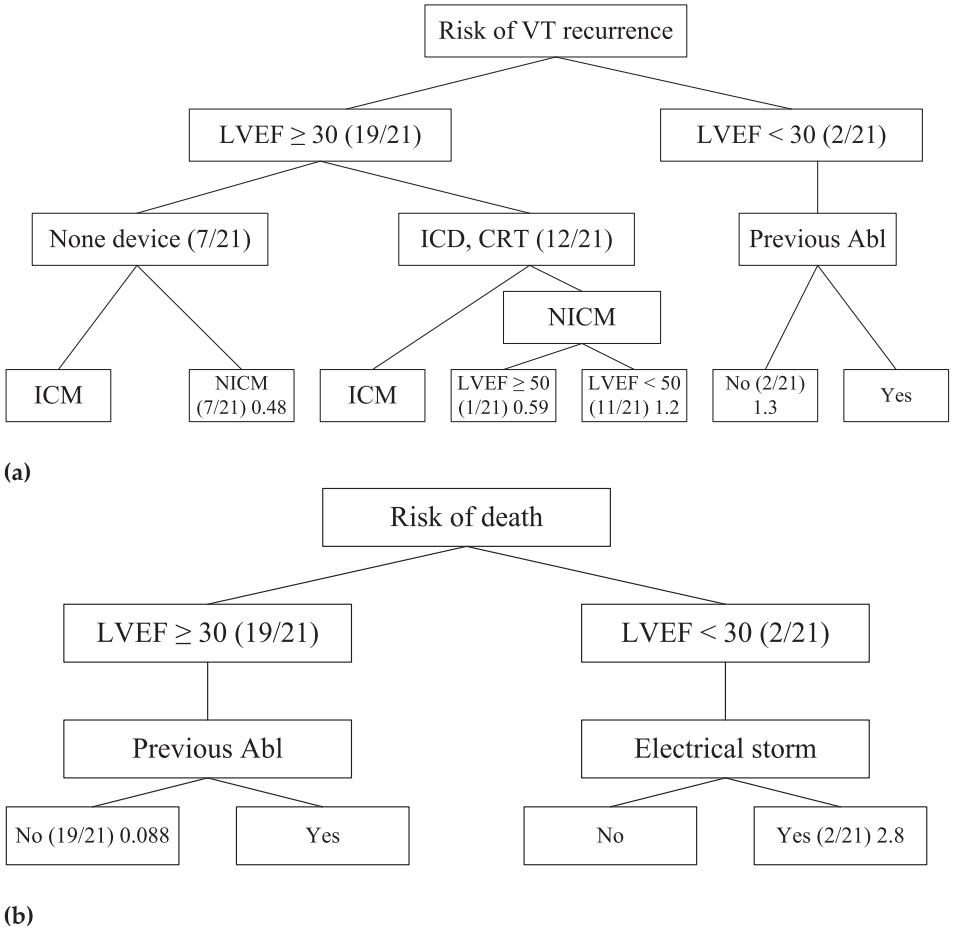

Fig. 1. I-VT scores. (a) the risk of VT recurrence; (b) the risk of death. BSA = body surface area; EF = ejection fraction.

patients had a preoperative ICD implanted (n = 3). Although the mean ejection fraction (EF) was approximately 40 %, while the PAINESD risk score [25,26] and the I-VT scores (Fig. 1) were not high [27], all patients developed hypotension during episodes of VT, with varying degrees of dizziness, fading vision, and syncope. Given the need for repeated intraoperative pacing to induce and maintain VT episodes for labeling and ablation, it is recommended that such patients undergo intra-operative ECMO support even when clinical cardiac function is stable and EF values are normal (Table 1). Patients with contraindications to peripheral ECMO were excluded. Under general anesthesia, before mapping, VA-ECMO was implanted through a femoral arteriovenous incision on one side, while the contralateral side served as an access point for CA [28].

The final device was developed by combining MiECC and ECMO. Additionally, the centrifugal pump (Sorin Revolution, LivaNova PLC, Arvada, CO) and the oxygenator (CAPIOX FX25, Terumo, Tokyo, Japan) with custom arteriovenous tubing (Shandong Wego New Life Medical Devices CO. LTD, Weihai, China) constituted the ECMO device. Furthermore, in order to regulate the temperature a variable-temperature water tank was connected.

The ECMO device was pre-programmed, as shown in Fig. 2a, and was operated as shown in Fig. 2b. This setup allowed us to perform

Table 1
Patient characteristics: the PAINESD risk score and the I-VT Score.

CASE	Gender (Male/Female)	Age (Years)	Height (cm)	Weight (kg)	BSA (m^2)	Cardiac disease substrate	Previous ablation	Other diseases
1	F	61	156	52	1.48	Paroxysmal ventricular tachycardia, coronary disease	None	Diabetes
2	M	64	182	86	2.05	Ventricular arrhythmia, dilated cardiomyopathy, coronary disease	None	Hypertension
3	M	51	180	81.5	1.99	Acute myocardial infarction, hypertrophic cardiomyopathy	None	Hypertension
4	M	69	173	72.7	1.83	Ventricular arrhythmia, coronary disease	None	Hypertension, Diabetes
5	M	69	165	70	1.75	Ventricular tachycardia, myocardiopathy, coronary disease	None	Hypertension
6	M	54	168	69	1.76	Coronary disease, acute myocardial infarction, paroxysmal ventricular tachycardia	None	Diabetes
7	M	67	171	77.5	1.88	Ventricular arrhythmia, coronary disease	None	None
8	M	64	178	67.8	1.8	Ventricular arrhythmia, dilated cardiomyopathy	None	Abnormal renal function
9	M	71	167	51.2	1.52	Paroxysmal ventricular tachycardia, coronary disease	None	Diabetes
10	M	64	173	77	1.96	Ventricular arrhythmia, coronary disease	None	None
11	M	51	177	73	1.93	Ventricular arrhythmia, dilated heart disease, coronary disease	None	Abnormal renal function, diabetes
12	F	67	156	43.5	1.36	Ventricular arrhythmia, dilated cardiomyopathy	None	Abnormal renal function, hypotension
13	M	72	170	40	1.4	Ventricular arrhythmia, coronary disease	None	None
14	F	64	156	47	1.46	Ventricular arrhythmia, coronary disease	None	None
15	F	57	156	72	1.78	Ventricular arrhythmia, coronary disease	None	None
16	M	73	174	75	1.94	Ventricular arrhythmia, cardiomyopathy	None	None
17	M	57	169	82	2	Ventricular arrhythmia, coronary disease	None	Hypertension
18	M	55	172	73	1.9	Paroxysmal ventricular tachycardia, coronary disease	None	Hypertension
19	M	42	175	78	1.98	Ventricular arrhythmia, dilated heart disease, coronary disease	None	None
20	F	66	160	57	1.61	Paroxysmal ventricular tachycardia, coronary disease	None	Hypertension, Diabetes
21	M	53	168	67.5	1.81	Ventricular arrhythmia, cardiomyopathy	None	Hypertension

CASE	EF Pre-intervention (%)	NYHA classification	PAINESD risk score
1	52	III	18
2	42	III	15
3	54	II	6
4	35	IV	21
5	50	II	9
6	41	III	15
7	37	III	15
8	40	III	9
9	38	III	18
10	43	IV	15
11	38	II	9
12	22	II	11
13	30	II	9
14	36	II	9
15	43	II	6
16	42	II	3
17	42	II	6
18	42	I	6
19	25	III	15
20	38	III	18
21	40	II	6

BSA = body surface area; EF = ejection fraction.

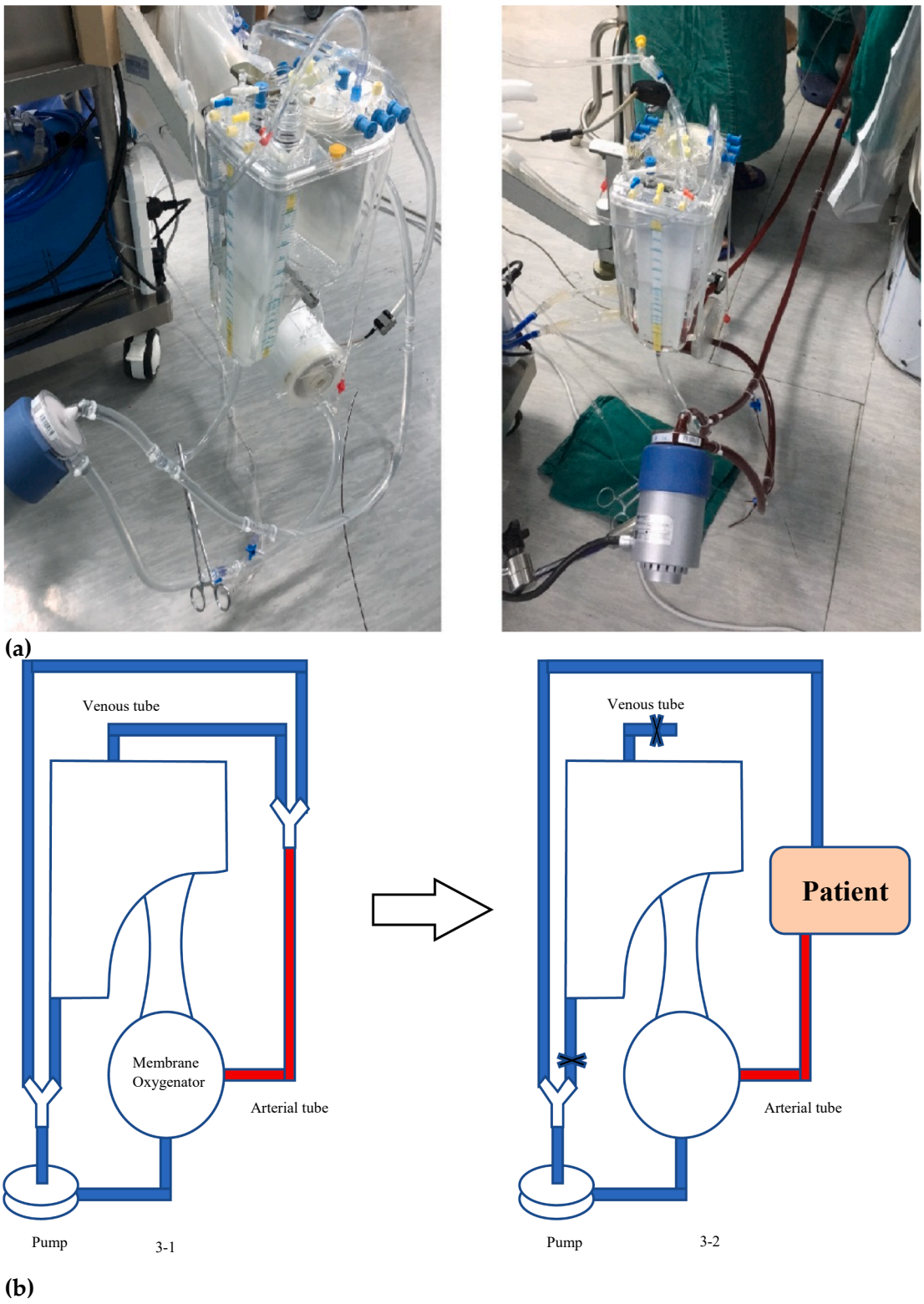

Fig. 2. ECMO device setup. (a) the pre-programmed ECMO device; (b) the operating ECMO device. ECMO, extracorporeal membrane oxygenation.

cardiopulmonary bypass (CPB) if the patient required open chest surgery. Additionally, the VA-ECMO device was filled with approximately 1000 mL of crystal and colloid in a 1:2 ratio. Then, the surgeon incised the skin near the left inguinal region and performed careful dissection to expose the left femoral artery and vein. For purging and dissecting the vessels, an Ethicon 5–0 wire (Johnson & Johnson, OH, USA) was used, then the femoral vein was implanted with a 17–19-Fr Bio-Medicus step cannula, which was delivered to the right atrial entrance under X-ray fluoroscopy. Simultaneously, a 15–17-Fr Bio-Medicus cannula was implanted in the femoral artery (Fig. 3).

In addition, intraoperative heparin was applied for anticoagulation (100 units/kg), and the activated clotting time (ACT) was maintained between 250 and 300 s to prevent thrombus formation. Coagulation indicators, blood gas analysis, neuron-specific enolase, and other

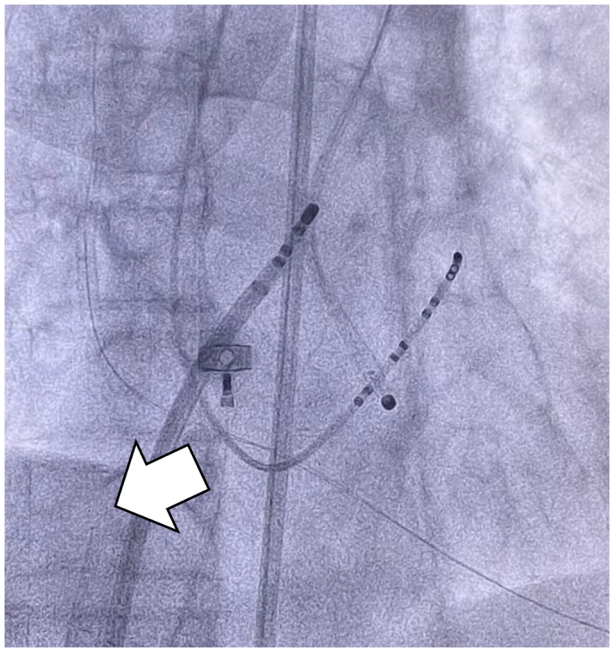

Fig. 3. Radiographic image of the ECMO inflow cannula. ECMO, extracorporeal membrane oxygenation.

information were monitored during the procedure (Table 2). After heparinization, the ECMO system was activated for full flow, with the water tank kept at 36 °C to maintain warmth. ECMO flow was controlled to keep the cardiac index above 2.0 (2.5–3.0 L/min). If the patient experienced fluctuations in blood pressure, the centrifugal pump speed was increased to maintain a higher mean arterial pressure (MAP). For prompt adjustments various medications were used, such as phenylephrine and norepinephrine, and replenishing blood volume [29]. Moreover, the MAP was maintained above 60–70 mmHg during the entire mapping procedure.

After the VT CA, ECMO was discontinued immediately, as all patients were hemodynamically stable. Furthermore, protamine neutralization was performed postoperatively (protamine/heparin neutralization dose ratio: 0.25–0.5/1). To improve hemoglobin levels, the residual blood in the ECMO circuit was transfused back to the patient after ECMO intubation was discontinued. After weaning from ECMO, the patient was transferred to the coronary care unit (CCU) for further clinical observation.

2.1. Statistical methods

Pre-operative and postoperative blood tests including routine blood tests, liver and kidney function tests, coagulation function tests, ACT tests, and blood gas analysis were performed. Laboratory values are expressed as mean ± SD values at baseline (preoperative) and mean ± SD value after the procedure; probability values reflect differences in mean values before vs. after the procedure (paired *t*-test). All statistical analyses were performed using SPSS 12.0 (SPSS Inc, Chicago, IL). A paired *t*-test P value < 0.05 was considered statistically significant.

3. Results

The data showed no differences in blood routine lactic acid and creatinine levels during and after radiofrequency ablation (Table 3). Moreover, hemoglobin levels decreased because of hemodilution during the operation, but returned within a safe range postoperatively. In

Table 3
Patient test results.

Test results	Preoperative	Postoperative	P
ACT	318 ± 42	162 ± 26	<0.01
INR	1.28 ± 0.09	1.30 ± 0.10	>0.99
PT(s)	13.87 ± 0.94	14.1 ± 1.08	0.97
D-D (mg/L)	0.39 ± 1.13	0.72 ± 0.89	0.67
Anti-Xa	1.83 ± 0.21	0.14 ± 0.09	<0.01
Lac	1.37 ± 0.51	1.65 ± 1.23	0.39
Hb	138.65 ± 17.23	125.94 ± 14.96	0.02
PLT	185.1 ± 42.44	184.6 ± 62.99	0.97
Cr	102.05 ± 29.13	92.76 ± 19.69	0.27
BUN	7.03 ± 2.46	9.71 ± 3.19	0.01
ALT	36.30 ± 33.33	45.62 ± 51.34	0.1
AST	32.84 ± 18.36	50.50 ± 40.37	0.14
cTnI	1.40 ± 1.59	0.01 ± 0.01	0.10

ACT = activated clotting time; INR = international normalized ratio; PT = prothrombin time; D-D = D-dimer; Anti-Xa = The anti-factor Xa; Lac = lactate; Hb = hemoglobin; PLT = platelet; Cr = creatinine; BUN = blood urea nitrogen; ALT = alanine transaminase; AST = aspartate aminotransferase; cTnI = cardiopulmonary troponin I.

Table 2
Patient intraoperative conditions.

CASE	Cannulas (Fr)		ECMO flow (L/min)	ECMO time (min)	Mapping		RFA time (s)	Ablation result
	Vein	Artery			Activation	Substrate		
1	21	17	3.9	180	√	√	300	Success
2	23	17	5.3	65	√	√	400	Success
3	21	17	5.2	215	×	√	200	Failed
4	21	17	4.8	285	√	√	300	Success
5	21	17	4.6	205	√	√	300	Success
6	21	17	4.6	210	√	√	200	Success
7	22	17	4.9	200	×	√	300	Success
8	21	17	4.7	270	√	√	200	Success
9	19	15	4.0	202	√	√	400	Success
10	21	15	5.0	190	√	√	500	Success
11	21	15	5.0	165	√	√	300	Success
12	19	15	3.6	90	√	√	300	Success
13	19	15	3.7	183	√	√	400	Success
14	21	15	3.8	195	√	√	600	Success
15	21	15	4.7	255	√	√	400	Success
16	21	17	5.1	415	×	√	300	Success
17	21	17	5.3	150	×	√	300	Success
18	21	17	5.0	245	×	√	300	Success
19	21	19	5.2	200	√	√	400	Success
20	19	15	4.2	175	√	√	600	Success
21	21	15	4.7	230	√	√	200	Success

addition, the antifactor Xa (anti-Xa) levels were increased due to the addition of heparin intraoperatively, and protamine neutralization was added postoperatively (protamine/heparin neutralization dose ratio: 0.2–0.5/1). Although ACT returned to normal values after surgery, anti-Xa levels were still 0.14 ± 0.09 U/mL, indicating that some heparin remained in the body and was slowly metabolized while the patients were in the CCU.

Among all cases, mechanism or substrate CA was not accomplished in only one patient. Successful ablation was achieved in 20 out of 21 patients (95 %) (Table 2). The median time for ECMO implantation was 206 min, while removal was performed within 1 h after ablation. In addition, 13 out of 21 patients (62 %) received an ICD as a preventive measure for sudden cardiac death [30].

Moreover, after treatment two patients experienced complications; one was infused with two units of red blood cells after returning to the ward owing to intraoperative bleeding from the femoral vein and the other patient experienced delayed recovery from anesthesia.

All patients made complete recovery and were discharged (Table 4), the median hospital stay was 17 days (8–27), while the total readmission rate was approximately 24 %. Furthermore, one patient was readmitted approximately 2 months after discharge with symptoms of heart failure. After treatment, the patient was discharged, showing recovery. In addition, a second patient was readmitted because of abnormal liver function and transferred to another hospital for further treatment. Three other patients were readmitted for ICD implantation. Importantly, all patients were alive at the 1-year follow-up.

4. Discussion

Radiofrequency ablation is a common non-pharmacological clinical treatment method for arrhythmia [31]. An ablation catheter is inserted through a puncture point into a specific part of the heart, and a high-frequency current is passed through the catheter, causing local myocardial tissue degeneration and inactivation through thermal effects-coagulation necrosis. This destroys the re-entry pathway or ectopic excitation focus of the arrhythmia, thereby achieving the purpose of the treatment [32]. However, the radiofrequency ablation process is not completely risk-free and may cause refractory ventricular arrhythmia, electrical storm, and even cardiogenic shock, which poses a significant threat to the patient's life [2]. Even with the use of various mechanical devices, there is significant risk and potential for complications [11,33]. Some of the patients in our study population were not classified as high-risk patients preoperatively, but intraoperative hemodynamic instability made it difficult for the surgeon to perform successful CA procedures, resulting in poor postoperative outcomes and a high recurrence rate. Previous data from our center has shown that patients had a recurrence rate of 20 % one year postoperatively. The use of VA-ECMO reduces the risk to a certain extent, allowing the surgeon to perform the entire CA procedure stably [34,35]. Substrate-based ablation was attempted in addition to substrate mapping of critical isthmuses as detailed in the Methods. However, given recurrent inducibility, a pre-emptive ECMO approach was used for patient stability during further mapping and ablation. This made it easier for the surgeon to perform procedures such as activation mapping, which allows for more thorough CA and a better prognosis. Previous strategies for substrate ablation have encountered challenges in establishing a clear connection between clinical VT and "subjectively determined" substrate ablation. Additionally, the lack of a reliable electrophysiological endpoint has hindered the ability to repeat activation mapping of VT after substrate ablation. The aim of the present study was to address these limitations by providing the surgeon with increased confidence in inducing clinical VT, supported by appropriately prepared hemodynamics. This, in turn, will enable the surgeon to establish a causal link between the identified substrate and labeled VT, thereby facilitating a more targeted ablation approach with a definitive endpoint.

Compared to other studies that showed a survival rate of 38 %–98.5 % [4,5], we had a satisfactory postoperative survival rate and a 12-month long-term survival rate. The study reported fewer circulatory and neurological complications compared with other studies [1,16,30]. A proper intraoperative ECMO flow rate and MAP was maintained, keeping the patient's left cardiac afterload at a low level, as well as achieving normal preoperative and postoperative lactate levels (Table 3), suggesting that the VA-ECMO support was adequate for organ and tissue perfusion [36]. The mean EF of our patients was higher than 30 % (Table 1), but patients often had preoperative arrhythmia, hemodynamic instability, and/or electrical storm. Even in such high-risk cases, the study achieved a high success rate and low mortality (Table 4), due to the implantation of modified MiECC combined with the ECMO system preoperatively [5,37].

The developed VA-ECMO device incorporates the MiECC system, which includes a hard-shell reservoir that can be converted to an open system if necessary during the procedure, which facilitates the management of intraoperative complications, ensures surgical safety, and serves as a bridge to respiratory and circulatory support or cECC. Thus, if a patient's condition requires a shift to ECMO support or cardiac surgery, the system can be switched directly without reintubation. Furthermore, anticoagulation with low doses of heparin reduces bleeding complications [37], and coagulation indicators such as anti-Xa are monitored preoperatively for better control of anticoagulation. Additionally, the cost of the device is lower, being approximately only one-fifth of the expense of conventional VA-ECMO.

The modified VA-ECMO setup was easy to operate and cheaper than standard ECMO, allowing the transition to surgical operations. Moreover, a lower dose of intraoperative heparin anticoagulation was used to reduce the possibility of bleeding. Most importantly, the prognosis of the cases in our hospital was good.

4.1. Limitations

During the experiment, some limitations were encountered. First, it comprised a single-center, retrospective, non-randomized analysis. Additionally, it was unable to quantify specific variations in treatment regimen in each patient. The primary objective of this study was to assess the safety and feasibility of using ECMO as an aid during VT CA. However, it did not specifically address the safety of this approach in high-risk populations. Moreover, the sample size was relatively small; but the high survival rates and few recent complications may be related to the moderate cardiac function in some patients. Finally, future larger prospective randomized trials with longer follow-ups and more detailed data collection are necessary to determine whether ECMO implantation leads to an increase or decrease in complications among high-risk VT patients compared to those who do not undergo implantation. This will also help to better evaluate the role of ECMO in CA of malignant VT.

Table 4
Patient outcomes.

Outcomes	Rate
Success rate of catheter ablation	95 % (n = 20)
ICD implantation rate	62 % (n = 13)
VT recurrence rate	5 % (n = 1)
Readmission rate	24 % (n = 5)
LVAD implantation rate	0 (n = 0)
Heart transplant rate	0 (n = 0)
6-month survival rate	100 % (n = 21)
12-month survival rate	100 % (n = 21)

Values are presented as mean ± SD or as n (%).
ICD = implantable cardioverter defibrillator.
LVAD = left ventricular assist device.

5. Conclusions

In conclusion, the modified VA-ECMO system, combined with the

MiECC, helps restore systemic circulation in patients with electrical storm, allowing for effective organ perfusion that provides greater electrical stability during VT CA. Pre-insertion of VA-ECMO can achieve better results.

CRediT authorship contribution statement

Shanfeng Zhang: Conceptualization, Writing – original draft. **Yueh-ting Chou:** Conceptualization, Writing – review & editing. **Jinlin Zhang:** Methodology, Resources, Supervision. **Jin Chen:** Methodology, Data curation. **Yiming Xiong:** Validation, Formal analysis. **Juan Lu:** Validation, Formal analysis. **Chao Chen:** Validation, Investigation. **Yue Xu:** Software, Visualization. **Yan Liu:** Supervision, Project administration.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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