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Measurement of End-tidal Carbon Dioxide in Patients with Cardiogenic Shock Treated Using a Percutaneous Cardiopulmonary Assist System

Keiji Tanaka[1], Naoki Sato[1], Takeshi Yamamoto[1], Koichi Akutsu[1], Masahiro Fujii[1] and Teruo Takano[2]

[1]Division of Intensive and Coronary Care Unit, Nippon Medical School
[2]First Department of Internal Medicine, Nippon Medical School

Abstract

We have reported that percutaneous cardiopulmonary assist systems (PCPS) are effective in treating life-threatening cardiogenic shock that is intractable to treatment with intraaortic balloon pumping (IABP). However, there are few clinical indices that can be used to evaluate the effectiveness of PCPS. End-tidal carbon dioxide (ET-CO_2) content reflects pulmonary blood flow. We monitored ET-CO_2 continuously and determined whether we could use it as a new index to evaluate the effectiveness of PCPS. Seventeen patients with cardiogenic shock were intubated and evaluated by ET-CO_2 monitoring during PCPS. The etiology of shock included acute myocardial infarction (n=10), acute myocarditis (n=2), recent coronary artery bypass graft (n=1), cardiac rupture (n=1), hypertrophic obstructive cardiomyopathy complicated by ventricular fibrillation (n=1), left atrial myxoma (n=1) and artificial valve malfunction (n=1). PCPS was extremely effective in 10 of 17 patients (58.8%), and they recovered from the cardiogenic shock. The remaining 7 patients did not recover from shock, and died during PCPS. Six of ten patients who recovered from shock were successfully weaned from PCPS and 4 patients had good long-term survival. In the cases where PCPS was effective, the ET-CO_2 measured soon after the beginning of PCPS was significantly higher than in the cases in which PCPS was ineffective. Furthermore, the ET-CO_2 content increased gradually with the improvement in hemodynamics. In contrast, ET-CO_2 content remained low if PCPS was not effective. The ET-CO_2 represents a useful predictor of survival or death and is also a good index for weaning in patients treated with PCPS.
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Key words: end-tidal carbon dioxide (ET-CO_2), percutaneous cardiopulmonary assist system (PCPS), cardiogenic shock

Introduction

We have previously reported that the percutaneous cardiopulmonary assist system (PCPS) is effective for treating extremely serious cardiogenic shock that is refractory to intraaortic balloon pumping (IABP)[1]. However, there are few

Correspondence to Keiji Tanaka, MD, Director of Division of Intensive and Coronary Care Unit, Nippon Medical School, 1–1–5 Sendagi, Bunnkyo-ku, Tokyo 113–8603, Japan
E-mail: k-tanaka@nms.ac.jp
Journal Website (http://www.nms.ac.jp/jnms/)

Table 1 Demographics and Clinical Characteristics

No	Age	Gender	Diagnosis	PCSP Mean Duration (hour)	PCSP Pump Flow (L/min)	PCSP Effective	PCSP Weaned	Other Treatments	Outcome
1	64	F	AMI	51.25	1.2 ～ 2.5	YES	YES	IABP, CHDF, RV pacing	Died
2	57	M	AMI	95.33	0.6 ～ 2.4	YES	YES	IABP	Died
3	21	F	myocarditis	114.77	1.5 ～ 2.0	YES	YES		Alive
4	56	M	AMI	48.33	2.4 ～ 2.8	YES	YES	IABP, CHDF, PCI	Alive
5	58	F	LA Myxoma	39.67	1.5 ～ 2.2	YES	YES	IABP, Operation	Alive
6	58	M	Valve malfunction	208.50	2.0 ～ 4.0	YES	YES	IABP, CHDF, Re-AVR	Alive
7	12	F	myocarditis	65.10	0.5 ～ 2.1	YES	NO	IABP, CHDF, RV pacing	Died
8	56	M	AMI	175.95	1.8 ～ 3.0	YES	NO	IABP, CHDF	Died
9	38	M	HOCM (Vf)	45.85	2.1 ～ 3.0	YES	NO	IABP, CHDF	Died
10	76	M	AMI	59.75	1.8 ～ 3.0	YES	NO	IABP, CHDF, PCI	Died
11	81	M	AMI	10.50	1.6 ～ 3.0	NO	NO	IABP	Died
12	63	M	postCABG	16.70	2.5 ～ 2.8	NO	NO	IABP	Died
13	67	M	AMI (LV rupture)	1.97	2.5 ～ 3.0	NO	NO		Died
14	65	M	AMI	17.50	1.8 ～ 2.0	NO	NO	IABP	Died
15	76	M	AMI	6.42	1.5 ～ 2.0	NO	NO	IABP	Died
16	54	F	AMI	4.58	1.5 ～ 2.2	NO	NO	IABP, PCI	Died
17	71	F	AMI	8.50	1.5 ～ 2.5	NO	NO	IABP, CHDF, PCI	Died

AMI: Acute Myocardial Infarction, HOCM: Hypertrophic Obstructive Cardiomyopaty, Vf: Ventricular Fibrillation, IABP: Intra-aortic Balloon Pumping, LA: Left Atrium, RV: Right Ventricle, CHDF: Continuous Hemodiafiltration, PCI: Percutaneous Coronary Intervention, Re-AVR: Aortic Valve Replacement (redo), CABG: Coronary Artery Bypass Graft

clinical indices that can be used to evaluate the effectiveness of PCPS. Hemodynamic measurements using a Swan-Ganz catheter or echocardiography do not reflect actual pulmonary blood flow or cardiac output in patients treated by PCPS because of venous drainage from the right atrium.

The end-tidal carbon dioxide (ET-CO_2) content reflects pulmonary blood flow[2,3]. The ET-CO_2 has been shown to correlate with cardiac output during and after cardiopulmonary resuscitation (CPR)[4,5]. Active compression-decompression cardiopulmonary resuscitation increases ET-CO_2[4]. ET-CO_2 is also an accurate predictor of coronary perfusion pressure[6,7]. However, in patients who survive resuscitation, the ET-CO_2 content is not affected by either technique[8,9]. Levine et al.[10] reported that the ET-CO_2 content measured during resuscitative efforts is a predictor of death from cardiac arrest in patients with electrical activity but no pulse.

In this study, we monitored ET-CO_2 continuously and determined whether we could use it to evaluate the effectiveness of PCPS in the setting of severe cardiogenic shock.

Materials and Methods

Study Design

This study is a retrospective study in which we always paid attention to ethical considerations regarding all patients.

Patients

From March 1996 to December 2002, 17 patients with profound cardiogenic shock underwent PCPS. The age of the patients ranged from 12 to 81 years. Among these cases, 11 were men and 6 were women. Eleven had acute myocardial infarction (1 resulting in cardiac rupture), 2 had fulminant myocarditis and 1 had hypertrophic obstructive cardiomyopathy (HOCM) complicated by ventricular fibrillation (**Table 1**).

All patients had cardiogenic shock and were

Fig. 1 End-tidal carbon dioxide measurements were performed by mainstream sampling with a lightweight sensor attached directly to the endotracheal tube (Cosmos 7100, Novametrix Medical Systems).

treated with dopamine and dobutamine at doses exceeding 10 μg/kg/min. IABP therapy was instituted in 15 of the patients. Four patients with acute myocardial infarction underwent percutaneous transluminal coronary angioplasty. Eight patients with anuria received continuous hemodiafiltration (CHDF). Two patients with advanced AV block received temporary RV pacing. Surgical procedures were performed in three patients to treat cardiac rupture, left atrial myxoma, or artificial valve malfunction, respectively.

Definition of Cardiogenic shock

Cardiogenic shock was confirmed by the following clinical criteria of the Myocardial Infarction Research Unit (MIRU)[11]: (1) A systolic arterial pressure less than 90 mmHg or 30 mmHg below the previous basal level. (2) Evidence of reduced blood flow as shown by (all should be present): (a) Urine output less than 20 m*l*/hour, preferably with a low sodium content. (b) Impaired mental function. (c) Peripheral vasoconstriction associated with a cold, clammy skin.

Effect of the PCPS and Group Classification

The PCPS system used in all cases consisted of a centrifugal pump manufactured by St. JUDE Medical (Lifesteam USA), a hollow-fiber oxgenator (Kurare Inc. Japan) and connection tubes. With use of the Seldinger technique, Teflon cannulas were inserted into the femoral artery (14 F) and vein (17 F) and the tip of the venous cannula was placed in the right atrium.

PCPS was performed as a circulatory assist procedure in 17 patients with profound cardiogenic shock. The mean blood flow (max) achieved with PCPS was 2.6 L/min (range: 2.0 to 4.0 L/min). Patients were maintained on PCPS for a mean duration of 57 hours 6 minutes (range 1.97 to 208.50 hours). PCPS was extremely effective in 10 (effective group: BP increased over 90 mmHg and urine output increased over 20 m*l*/hr during one hour) of the 17 patients (58.8%), and they recovered from the cardiogenic shock. Six (weaned group) of ten patients who recovered from shock were successfully weaned from PCPS and 4 patients (23.5%) had good long-term survival. Another 4 patients (dependent group) who recovered from the shock were not weaned from PCPS and died. The most common cause of death in the 6 who did not survive was multi-organ failure (MOF) complicated by infection. The remaining 7 patients (ineffective group) did not recover from cardiogenic shock, and died during PCPS.

Measurement of ET-CO_2

All patients had undergone endotracheal intubation and received mechanical assist ventilation. The endotracheal tube was connected to a combined pulse oximeter–capnograph (Cosmos 7,100, Novametrix Medical Systems USA). ET-CO_2 measurements were performed by mainstream sampling with a lightweight sensor attached directly to the endotracheal tube (**Fig. 1**) under mechanical assist ventilation.

The initial measurement of ET-CO_2 was made soon after the start of PCPS and the highest value during one minute was adopted. It was performed repeatedly until PCPS was discontinued. Measurements of hemodynamic parameters (arterial blood pressure, heart rate, urine production) were performed simultaneously. Because of the unstable condition of the patients, these data could not be recorded before starting PCPS.

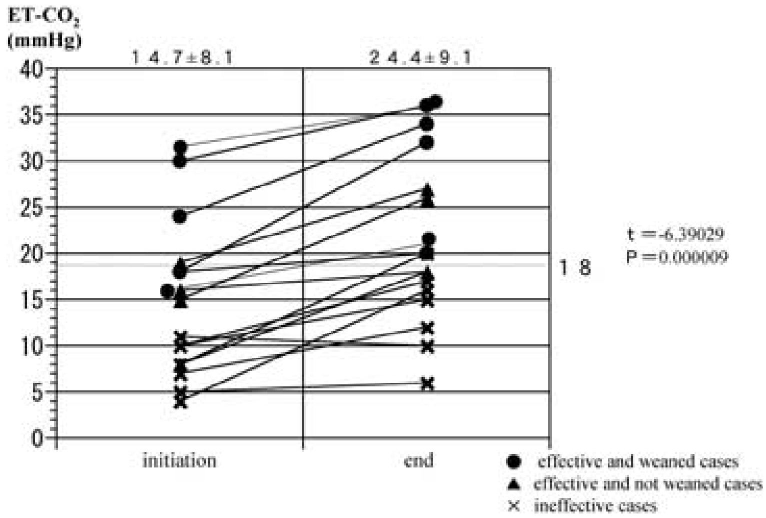

Fig. 2 Changes in $ET\text{-}CO_2$ between the initiation of PCPS and end of PCPS use.
(●: effective and weaned cases, ▲: effective but not weaned cases, ×: ineffective cases)

Statistical Analysis

The initial measurement values and the last measurement values recorded just before the discontinuation of PCPS are presented as the mean ± standard deviation. Differences between the two measurements were assessed by paired Student's t test. To assess the difference of $ET\text{-}CO_2$ and hemodynamic parameters in the three groups above mentioned (effective group, weaned group, ineffective and dependent group), Student's t test and Fisher's exact test were used. A p value of <0.05 was considered significant.

Results

In all patients, the $ET\text{-}CO_2$ measured soon after the initiation of PCPS was 14.7 ± 8.1 mmHg and increased to 24.4 ± 9.1 mmHg at the final measurements ($p = 0.00009$: **Fig. 2**). The initial $ET\text{-}CO_2$ clearly discriminated between the group that responded to PCPS and the group in which PCPS was ineffective, averaging 19.5 ± 7.0 mmHg (range: 8 to 31 mmHg) in the effective group and 7.9 ± 2.7 mmHg (range: 4 to 11 mmHg) in the ineffective group ($p = 0.0064$). The final $ET\text{-}CO_2$ also discriminated between the effective group and the ineffective group ($p = 0.0405$), averaging 26.8 ± 7.3 mmHg (range: 18 to 36 mmHg) in the effective group and 13.7 ± 4.7 mmHg (range: 6 to 20 mmHg) in the ineffective group. The result of Fisher's exact test with the initial $ET\text{-}CO_2$ dichotomized at a value of 10 mmHg was significant ($p = 0.0278$). The result of the same test with the final $ET\text{-}CO_2$ dichotomized at a value of 18 mmHg was also significant ($p = 0.0333$).

The initial $ET\text{-}CO_2$ in the PCPS dependent group (14.5 ± 4.7 mmHg) was lower than the content in the weaned group (22.8 ± 6.5 mmHg. $p = 0.0028$). The final $ET\text{-}CO_2$ was 22.3 ± 4.9 mmHg in the dependent group and 29.8 ± 7.4 mmHg in the weaned group, but the difference between the two groups was not significant ($p = 0.1184$). All patients in the weaned group had an initial $ET\text{-}CO_2 > 18$ mmHg and all patients in the dependent group had a final $ET\text{-}CO_2$ <28 mmHg.

The $ET\text{-}CO_2$ of a representative patient (Case 7) in the dependent group illustrates changes that are dependent on pump flow (**Fig. 3**; left). In contrast, a high $ET\text{-}CO_2$ observed in one patient in the weaned group was hardly influenced by changes in pump flow (**Fig. 3**; right).

The hemodynamic parameters are summarized in **Table 2**. The maximum blood pressure (max BP) was extremely low before PCPS and increased significantly ($p = 0.0001$) from 46.8 ± 20.1 mmHg to 91.8 ± 25.3 mmHg during PCPS. The minimum blood pressure (min BP) also increased to 50.6 ± 20.6 mmHg

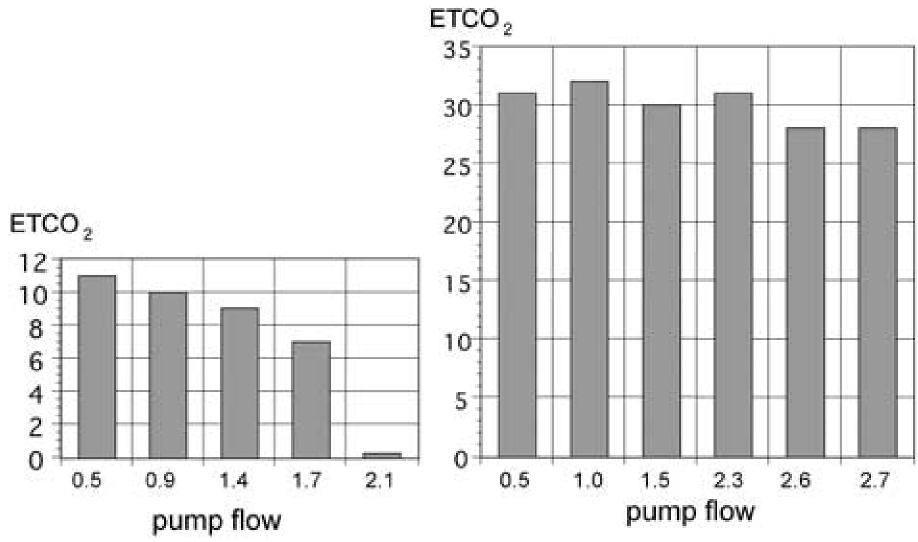

Fig. 3 Relationship between PCPS pump flow and ET-CO_2.
The ET-CO_2 of a patient (Case 7) in the dependent group revealed changes dependent on pump flow (left). In contrast, high ET-CO_2 were observed in one patient in the weaned group (Case 4); the ET-CO_2 was hardly influenced by changes in pump flow (right).

Table 2 The Changes in Hemodynamic and Blood Gas Parameters during PCPS

	pre PCPS	during PCPS	p value
	Hemodynamic parameters		
HR (/min)	98.3 ± 26.6	101.2 ± 28.6	0.5621
BPs (mmHg)	46.8 ± 20.1	91.8 ± 25.3	0.0001
BPd (mmHg)	25.0 ± 12.8	50.6 ± 20.6	0.0008
CVP (mmHg)	11.9 ± 4.8	10.4 ± 4.9	0.6842
UV (ml/hr)	3.0 ± 6.5	129.2 ± 157.8	0.0338
	Blood gas analysis		
pH	7.27 ± 0.15	7.42 ± 0.16	0.0416
PO_2 (mmHg)	198 ± 104	209 ± 73	0.9172
PCO_2 (mmHg)	36.0 ± 18.7	40.0 ± 23.5	0.5757
BE	− 12.0 ± 7.5	− 2.1 ± 11.4	0.0259
SaO_2 (%)	90.7 ± 26.0	99.5 ± 0.3	0.3139

from 25.0 ± 12.8 mmHg (p = 0.0008). There were no changes in heart rate (HR) or central venous pressure (CVP) during PCPS. The urine volume (UV) after PCPS was significantly greater than that before PCPS (p = 0.0338).

Fig. 4 shows changes of max BP and UV. Max BP was more highly increased in the two effective groups (weaned group and dependent group) than in the ineffective group but the difference between the weaned and dependent groups was not significant (left side). The UV was also significantly greater in the two effective groups than in the ineffective group during PCPS. After 6 hours of PCPS, the UV in the weaned group was greater than in the dependent group (right side) and the UV measured before the termination of PCPS in the weaned group was no different from that in the dependent group.

PCPS improved metabolic acidosis remarkably, but did not differ within the three groups.

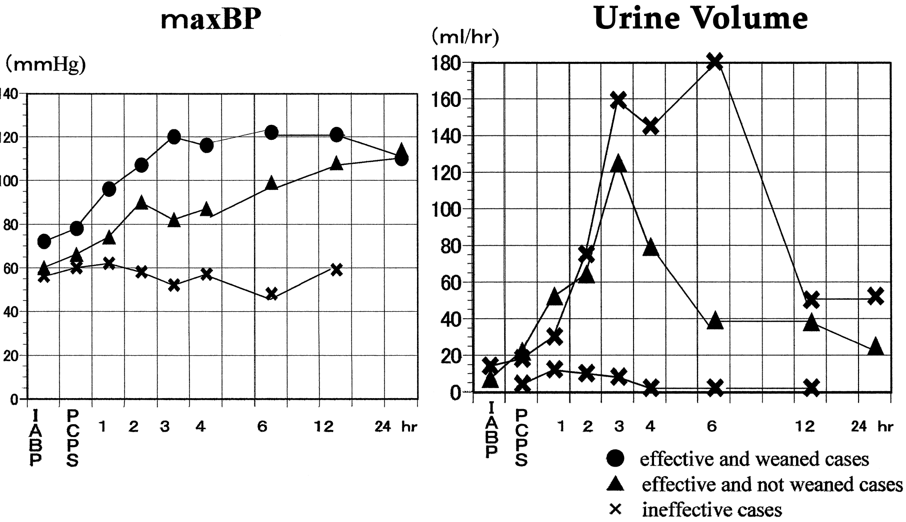

Fig. 4 Change of max BP and UV (Urine Volume) during PCPS.
(●: effective and weaned cases, ▲: effective but not weaned cases, ×: ineffective cases)

Discussion

The ET-CO_2 content is determined by carbon dioxide production, alveolar ventilation, and pulmonary blood flow[2,3]. The ET-CO_2 has been shown to correlate with cardiac output during and after cardiopulmonary resuscitation (CPR)[4,5]. Therefore, ET-CO_2 represents a useful predictor of survival after cardiac arrest[12-15]. Callaham et al. found that the initial ET-CO_2 content determined after prolonged cardiac arrest and cardiopulmonary resuscitation predicts survival, with values averaging 19 mmHg in survivors and 5 mmHg in nonsurvivors[12]. A threshold ET-CO_2 content of 15 mmHg in that study had the best sensitivity and specificity for identifying survivors with positive and negative predictive values of 91%. Levine et al. reported a threshold effect between 10 and 18 mmHg[10]. Specifically, no patient who had an ET-CO_2 content $<$10 mmHg survived. Conversely, in all patients in whom spontaneous circulation was restored, the ET-CO_2 increased to at least 18 mmHg before detectable changes in the vital signs.

Reichman et al. used PCPS in patients in whom standard cardiopulmonary resuscitation was ineffective or who had a fatal arrhythmia[16]. In such patients, PCPS supported cardiopulmonary function and allowed diagnostic and therapeutic interventions to be used. We also reported previously that PCPS is effective for the treatment of extremely serious cardiogenic shock[17,18] when IABP is not effective[1].

However, there are few clinical indices that can be used to measure the effectiveness of PCPS. Hemodynamic measurements using a Swan-Ganz catheter or echocardiography do not reflect true pulmonary blood flow or native cardiac output in patients receiving PCPS because of blood drainage from the right atrium to the femoral artery.

Even in the setting of shock, if minute ventilation is held constant, changes in the ET-CO_2 concentration will predominantly reflect pulmonary blood flow and indirectly, cardiac output[4,5]. Therefore, we hypothesized that the effectiveness of PCPS can be evaluated by measuring the ET-CO_2.

In our study, no patient who had an initial ET-CO_2 content $<$10 mmHg survived, in keeping with the findings of Levine et al.[10]. The initial ET-CO_2 content in the PCPS dependent group was also lower than the content in the weaned group. The final ET-CO_2 content was 22.3 ± 4.9 mmHg in the dependent group and 29.8 ± 7.4 mmHg in the weaned group, but the difference between the two groups was not significant. All patients in the weaned group had an initial ET-CO_2 $>$18 mmHg and all of the patients who could not be weaned from PCPS had a final ET-CO_2

<28 mmHg.

Based on these findings, PCPS is ineffective in treating patients if the initial ET-CO_2 is less than 10 mmHg. If the initial ET-CO_2 is less than 18 mmHg or the late ET-CO_2 does not exceed 28 mmHg, it can be predicted that the patient will not be weaned from PCPS. Therefore, ET-CO_2 represents a useful predictor of survival and also a good index for weaning in patients treated PCPS. Based on our results, various strategies for treating severe pump failure can be evaluated. In patients with extremely serious cardiogenic shock in which IABP therapy is not effective, PCPS should be attempted for several days. If PCPS is ineffective, then a ventricular assist device (VAD) should be used immediately. If native cardiac function does not recover and PCPS cannot be weaned, indication of a VAD implantation should be considered.

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