Research Article

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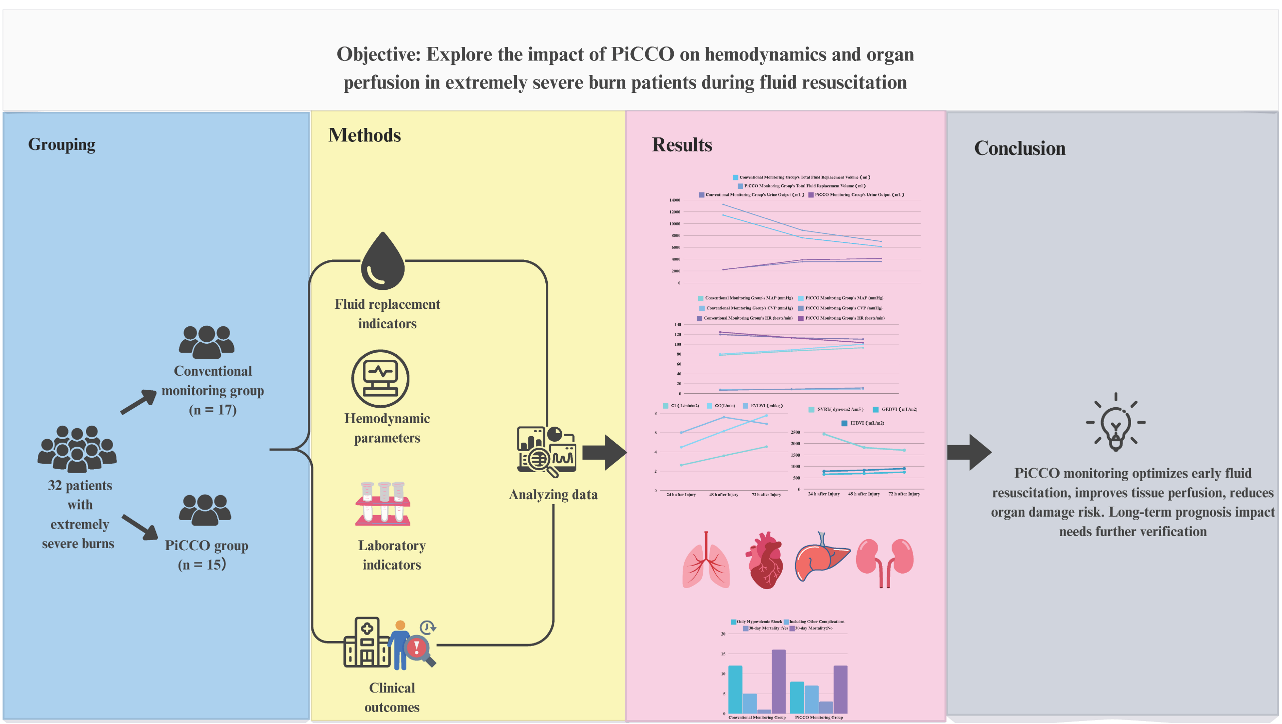
Graphical Abstract



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Research on the Impact of PiCCO-guided Precise Fluid Resuscitation on Hemodynamics and Organ Perfusion in Patients with Extremely Severe Burns

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Objective: To explore the impact of Pulse Indicator Continuous Cardiac Output (PiCCO) on hemodynamics and organ perfusion during fluid resuscitation in patients with extremely severe burns.

Methods: This study adopted a retrospective cohort study design. A total of 32 patients with extremely severe burns admitted to the Burn Department of the First Affiliated Hospital of Anhui Medical University from June 2022 to July 2024 were included. According to the monitoring methods, they were divided into a conventional monitoring group (n = 17) and a PiCCO group (n = 15). The basic data, fluid replacement indicators (total fluid replacement volume, urine output, fluid replacement coefficient, urine output per hour per kilogram of body weight), hemodynamic parameters [mean arterial pressure (MAP), central venous pressure (CVP), heart rate (HR), cardiac index (CI), cardiac output (CO), systemic vascular resistance index (SVRI), extravascular lung water index (EVLWI), global end-diastolic volume index (GEDVI), intrathoracic blood volume index (ITBVI)], laboratory indicators [lactate (Lac), base excess (BE), creatine kinase (CK), creatine kinase - MB (CK - MB), alanine aminotransferase (ALT), aspartate aminotransferase (AST), blood urea nitrogen (BUN), serum creatinine (Scr)] and clinical outcomes (complication incidence, 30 - day mortality, antibiotic use time, hospital stay and cost) of the two groups were compared. T-test, repeated-measures analysis of variance, Mann-Whitney U test, Bonferroni correction, chi-square test, and Fisher's exact probability method were used for statistical analysis.

Results: A comparison of the relevant indicators of patients with extremely severe burns between the PiCCO monitoring group and the conventional monitoring group showed no difference in the general conditions between the two groups ($P>0.05$). The total fluid replacement volume in the PiCCO monitoring group was higher in the first, second, and third 24h periods after injury ($P<0.05$), with no difference in urine output. The fluid replacement coefficient in the first and second 24h periods after injury was also higher ($P<0.05$), and the urine output per hour per kilogram of body weight was higher than the planned value, but there was no difference between the groups. At 72 hours after injury, the MAP and CVP in the PiCCO monitoring group were higher, and the HR was lower ($P<0.05$). At 72 hours after resuscitation, Lac and BUN in the PiCCO monitoring group were lower, and BE was higher ($P<0.05$), with no differences in other indicators. In the PiCCO monitoring group, multiple hemodynamic indicators such as CI, CO, SVRI, EVLWI, GEDVI, and ITBVI showed obvious changing trends over time after injury, and these changes were statistically significant ($P<0.05$), and these indicators returned to normal at different time points after injury. There were no significant differences in complications, 30-day mortality, antibiotic use days, hospital stay, and hospitalization costs between the two groups ($P>0.05$).

Conclusion: PiCCO monitoring can optimize the early fluid resuscitation of patients with extremely severe burns by precisely regulating the volume status, improving tissue perfusion, and reducing the risk of organ damage. However, its impact on long-term prognosis needs to be further verified by multi-center and large-sample studies.

Keywords: Extremely Severe Burns; Hemodynamics; PICCO; Fluid Resuscitation.

Abbreviations: PiCCO, Pulse Indicator Continuous Cardiac Output; TBSA, Total Body Surface Area; CI, Cardiac Index; CO, Cardiac output; EVLWI, Extravascular Lung Water Index; SVRI, Systemic Vascular Resistance Index; GEDVI, Global End Diastolic Volume Index; ITBVI, Intrathoracic Blood Volume Index; Lac, Lactic acid; BE, Base Excess; Scr, Serum Creatinine; BUN, Blood urea nitrogen; MAP, Mean Arterial Pressure; CVP, Central venous Pressure; HR, Heart Rate; CK, Creatine Kinase; CK - MB, Creatine Kinase - Myocardial Band; ALT, Alanine Aminotransferase; AST, Aspartate Aminotransferase; RAAS, Renin - Angiotensin - Aldosterone System; MODS, Multiple Organ Dysfunction Syndrome.

Introduction

Burn injury is a global public health problem. Approximately 265,000 people die from burns each year. Especially in low- and middle-income countries, the incidence and mortality rates of burns are higher[1-3]. The pathological process after a burn starts with the capillary leakage syndrome mediated by the inflammatory cascade reaction, which leads to hypovolemic shock and may further trigger multiple organ dysfunction syndrome or even death. As the burn area gradually expands and the burn depth continuously increases, the damage to the body becomes more severe. The incidence of shock significantly rises, and the time of its occurrence is also notably advanced. Extremely severe burns refer to burns with an area of more than 50% of the total body surface area (TBSA); or third-degree burns with an area of more than 20% of the TBSA. These burns often cause extremely serious damage to the body, triggering a series of complex and serious pathophysiological changes, such as systemic inflammatory

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reaction, massive loss of body fluids, tissue and organ damage, which greatly increases the difficulty of treatment and the risk of patient death. Therefore, for the early treatment of patients with extremely severe burns, timely and effective fluid resuscitation is of crucial importance. Early fluid resuscitation for patients with extremely severe burns faces a dual dilemma. The traditional protocol, relying on the formula from the Third Military Medical University and empirical monitoring indicators, has blind spots in hemodynamic assessment. Excessive fluid replacement is likely to cause serious complications such as pulmonary edema and cerebral edema[4], while insufficient fluid replacement will exacerbate organ hypoperfusion and may even lead to acute kidney injury, myocardial injury, etc [5, 6]. Thus, how to scientifically monitor early fluid replacement after injury and reduce related complications has become an urgent problem that needs to be solved.

In clinical practice, the evaluation of early hypovolemic shock after burns has long relied on traditional indicators such as urine output, electrocardiogram monitoring, blood oxygen saturation, and mental status[7, 8]. However, these indicators have obvious limitations. Clinical research and practice have shown that they may appear stable even when tissue perfusion and oxygenation have not been effectively improved, making it difficult to detect subtle changes in the condition, and they are insufficient in sensitivity[9]. This means that even if the vital signs and urine output are normal, it cannot be determined that the resuscitation is sufficient. There may be potential insufficient resuscitation, which can lead to the insidious progression of the condition, increase the risk of complications, and affect the prognosis of patients. Therefore, relying solely on traditional indicators cannot meet the clinical needs for accurate assessment and guidance of fluid resuscitation.

In recent years, hemodynamic monitoring techniques have been widely applied in the fluid management of critically ill patients [10]. The Pulse Indicator Continuous Cardiac Output (PiCCO) monitoring technique, with its advantages of simple operation and minimal invasiveness, has been widely used in clinical practice [11-13]. By integrating the transpulmonary thermodilution method and arterial waveform analysis, this technique overcomes the limitations of the traditional central venous pressure (CVP) that is interfered with by thoracic and abdominal pressure, heart diseases, and mechanical ventilation [14-16]. It can comprehensively and accurately monitor multiple key hemodynamic parameters [17, 18], including Cardiac Output (CO), Extravascular Lung Water Index (EVLWI), Cardiac Index (CI), and Systemic Vascular Resistance Index (SVRI), etc. [19, 20]. Among them, the Global End-Diastolic Volume Index (GEDVI) monitored by PiCCO has been confirmed by numerous studies to be an indicator with high sensitivity and good reproducibility [21, 22]. Moreover, since it is not affected by respiratory movements and myocardial compliance, it can more accurately reflect the preload of the heart. Currently, the PiCCO monitoring technique, with its unique advantages, has been widely applied in the fields of critical care medicine such as sepsis and heart diseases [23-25]. However, in the special and highly challenging clinical scenario of extremely severe burns, its application research is relatively limited. Although this technique is expected to provide more accurate guidance for the treatment of patients with extremely severe burns, the current number of relevant studies is insufficient, and both the depth and breadth need to be expanded. Therefore, an in-depth exploration of the impact of PiCCO-guided precise fluid resuscitation on the hemodynamics and organ perfusion of patients with extremely severe burns is of great significance for optimizing treatment strategies and improving the success rate of treating patients with extremely severe burns.

This study compares the effects of the PiCCO monitoring technique and the conventional monitoring technique in guiding fluid resuscitation for patients with extremely severe burns, explores the clinical value of the PiCCO monitoring technique in fluid resuscitation for patients with extremely severe burns and its role in preventing resuscitation-related complications, and provides a scientific basis for more accurate fluid replacement treatment in clinical practice.

Methods

This study was a retrospective analysis. After being approved by the hospital ethics committee according to the pre-set inclusion and exclusion criteria, the relevant clinical data of 32 patients with extremely severe burns admitted to the Burn Department of the First Affiliated Hospital of Anhui Medical University from June 2022 to July 2024 were collected. On the premise of ensuring the security of patient identity information without leakage, the clinical data could be used for analysis and research.

Inclusion and Exclusion Criteria

Inclusion criteria:

Total burn area > 50% TBSA or third - degree burn area > 20% TBSA; Age between 18 and 65 years old; Admitted to the hospital within 24 hours after injury and received fluid resuscitation; Complete fluid replacement and laboratory data within 3 days after injury.

Exclusion criteria:

Severe cardiovascular diseases (such as aortic aneurysm) or a history of vascular surgery; Puncture contraindications (local burns, infections, or coagulation abnormalities); Complicated with important organ dysfunction or pregnancy; Delayed resuscitation (> 24h) or incomplete data.

Clinical Data and Grouping

A total of 32 patients were enrolled in this clinical study, and were naturally grouped according to the actual clinical monitoring means: the routine monitoring group (n=17) received routine vital signs monitoring, while the PiCCO monitoring group (n=15) used PICCO detection technology for hemodynamic monitoring. The grouping was based on the clinical interventions actually received by the patients, and a non-randomized observational study design was used to minimize artificial selection bias. There were no statistically significant differences between the two groups in terms of general baseline data such as gender, age, weight, cause of injury, burn area, admission time, degree of inhalation injury and past history ($P>0.05$), indicating that the two groups were comparable. See Table 1.

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Table 1. Comparison of general data at admission between the two groups of patients with extremely

Group	Number of Cases	Gender		Cause of Injury		Age (years, $\bar{X}\pm s$)	Weight (kg, $\bar{X}\pm s$)	Admission Time (h, $\bar{X}\pm s$)	Total Burn Area (%TBSA, $\bar{X}\pm s$)	Inhalation Injury			Past Medical History	
		Male	Female	Flame	Hot Liquid					Mild	Moderate	Severe	Yes	No
Conventional Monitoring Group	17	16	1	16	1	47.59 ±9.88	73.82 ±11.71	5.18±3.13	83.06±9.37	8	2	7	3	14
PiCCO Monitoring Group	15	11	4	13	2	47.67 ±11.57	69.00 ±9.83	7.10±5.53	88.57±9.29	3	1	11	5	10
t value	-	-		-		-0.021	1.252	-1.190	-1.666	-			-	
P value	-	0.161*		0.589*		0.984	0.220	0.247	0.160	0.225*			0.423*	

Note: PiCCO denotes Pulse Contour Cardiac Output, and TBSA represents Total Body Surface Area. "—" signifies the absence of a statistical value, while "*" indicates the application of the Chi-square test.

Treatment Methods

General Treatment

Upon admission, intravenous access was immediately established for fluid resuscitation and anti-shock treatment in both groups of patients with extremely severe burns. Vital signs and fluid intake and output were closely monitored. Tracheotomy or fasciotomy was performed when necessary. The dressing - change or exposure therapy was selected according to the wound surface, and dressing changes were carried out regularly. Early esophagectomy (tangential excision) and skin grafting or debridement and skin grafting were performed. Broad-spectrum antibiotics (such as imipenem) were empirically used and then adjusted according to the culture results. Enteral and parenteral nutritional support was provided. Stress ulcers (such as omeprazole) and myocardial injury were prevented. Multidisciplinary cooperation and early rehabilitation intervention were carried out to ensure comprehensive treatment.

Fluid Replacement Method

Fluid resuscitation was carried out in both groups of patients with extremely severe burns according to the fluid replacement formula for the shock stage of the Third Military Medical University. The total fluid replacement volume = burn area (%)×body weight (kg)×1.5 (the sum of crystalloid and colloid) + 2000 ml (basic water). For patients with second-degree to third-degree burns, 1.5 ml of fluid was replenished per 1% burn area per kilogram of body weight, and the ratio of crystalloid to colloid was 2:1. At the same time, 2000 ml of 5% glucose was supplemented. Within the first 24 hours, half of the total volume was replenished in the first 8 hours, and then one-fourth of the total volume was replenished in the second 8-hour period and the third 8-hour period respectively; the total fluid replacement volume in the second 24 - hour period was half of the actual fluid replacement volume in the first 24 - hour period, the ratio of crystalloid to colloid remained unchanged, and 2000 ml of physiological requirement was infused at a constant speed.

Conventional Monitoring Group

A single-lumen central venous catheter from Arrow Company in the United States was used. After catheterization via the subclavian vein or femoral vein, the CVP was dynamically monitored through the GE DASH4000 monitoring system, and the pressure zero point was regularly calibrated.

PiCCO Monitoring Group

The prepared equipment and materials included a multi-function monitor (equipped with a PiCCO module), a double-lumen central venous catheter, a PiCCO thermodilution catheter device, a pressure sensor, 100 mL of sterile normal saline at 4°C - 8°C, 100 mL and 500 mL of sterile normal saline, a pressure bag, etc. Bedside deep-vein puncture and catheterization were performed. The right internal jugular vein was the first choice, followed by the subclavian vein or femoral vein. After inserting the double-lumen central venous catheter, the CVP lead wire was connected to continuously monitor the change of CVP, and the temperature probe was connected to the CO module through a three-way connector. After femoral artery catheterization, the PiCCO thermodilution catheter was inserted, and the PiCCO module was connected to the wire. Before monitoring, fluid replacement was stopped, the arterial and venous zero points were calibrated, and strict aseptic operation was performed. 15 mL of sterile normal saline at 4°C - 8°C was uniformly injected into the central venous catheter, with an injection time of 4 - 7 seconds, and repeated 3 times. The monitor automatically calculated the average value to obtain parameters such as EVLWI, GEDVI, ITBVI, and CI. After the monitoring system was set up, the circulatory status at the time of admission was immediately measured and recorded. Thereafter, monitoring was carried out every 8 hours, and the average value was taken from 3-time monitoring per day on the 1st - 3rd day after injury. The fluid replacement plan was dynamically adjusted based on PiCCO monitoring parameters (CI, CO, GEDVI, ITBVI, EVLWI, SVRI).

Statistical Indicators

(1) Fluid resuscitation indicators: The total fluid replacement volume and urine output of the two groups of patients in the first, second, and third 24h periods after injury were statistically analyzed. The fluid replacement coefficients in the first and second 24h periods after injury were calculated (formula: fluid replacement coefficient = [actual total fluid replacement volume - basic water]÷body weight÷total burn area), as well as the urine output per hour per kilogram of body weight. The above-measured data were compared with the standardized fluid replacement plan formulated by the Third Military Medical University (hereinafter referred to as the "planned value"). Among them, the planned values of the fluid replacement coefficients in the first and second 24h periods were 1.50 $mL \cdot kg^{-1} \cdot \%TBSA^{-1}$ and 0.75 $mL \cdot kg^{-1} \cdot \%TBSA^{-1}$ respectively, and the planned value of the urine output per hour per kilogram of body weight was 1.00 $mL \cdot kg^{-1} \cdot h^{-1}$.
(2) Vital sign indicators: MAP, CVP, and HR at 24h, 48h, and 72h after injury.
(3) Key resuscitation indicators and organ function indicators: Blood samples were collected at admission and after resuscitation (72h after injury) to detect the following indicators: Metabolism-related indicators: Lac and BE; Cardiac function indicators: CK and CK - MB; Liver function indicators: ALT and AST; Renal function indicators: Scr and BUN.
(4) Hemodynamic indicators: CI, CO, GEDVI, ITBVI, EVLWI, SVRI, etc. at 24h, 48h, and 72h after injury.
(5) Prognosis-related indicators: The complications, 30-day mortality after injury, antibiotic use days, hospital stay, and hospitalization costs of the two groups of patients were statistically analyzed.

Statistical Processing

In this study, key data were cross-validated against multiple sources of data, and the various data recorded were compared with the nursing records and medical records in the electronic medical record system to ensure data consistency. For missing data, we first assessed the missing mechanism, used multiple interpolation to process random missing data, and assessed the robustness of the processing method by sensitivity analysis. All reference time points (e.g., admission time, PiCCO monitoring start time) were aligned on a uniform timeline, and clinical parameters (e.g., CO, SVRI) were aligned with the PiCCO device output files to ensure consistency and accuracy of records.
Data were analyzed using SPSS 26.0 software to obtain data. Measurement data conforming to the normal distribution were expressed as $\overline{X}\pm s$. Repeated-measures analysis of variance was performed for the overall comparison between groups at multiple time points. The independent-sample t-test was used for the comparison between the two groups at each time point and between the two groups. The - sample t-test was used for the comparison between the data at each time point and the planned value and Bonferroni correction was performed for all; measurement data not conforming to the normal distribution were expressed as M (P25, P75), and the Mann - Whitney U test was used and Bonferroni - corrected; count data were expressed as frequencies and percentages, and the X2 test or Fisher's exact probability method was used (the software automatically ignored the statistical value). A difference was considered statistically significant when $P<0.05$, and a significant difference was considered to exist when $P<0.01$.

Table 2. Comparison of total fluid intake and urine output levels at various time points post-injury between the two groups of severely burned patients. ($\overline{X}\pm s$, ml)

Group	Number of Cases	Total Fluid Replacement Volume (ml)			Urine Output (ml)		
		1st 24 h	2nd 24 h	3rd 24 h	1st 24 h	2nd 24 h	3rd 24 h
Conventional Monitoring Group	17	11456.47 ±1741.62	7610.06 ±1516.02	6114.12 ±743.73	2249.12 ±691.37	3551.47 ±1254.11	3599.12 ±1509.90
PiCCO Monitoring Group	15	13260.00 ±1496.48	8878.33 ±1398.46	6990.67 ±1084.35	2198.00 ±351.22	3878.67 ±1210.92	4109.53 ±1283.67
t value	-	-3.120	-2.448	-2.694	0.258	-0.748	-1.023
P value	-	0.004	0.020	0.011	0.798	0.460	0.315

Note: PiCCO stands for Pulse Contour Cardiac Output.

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Results

Fluid Resuscitation Indicators

The total fluid replacement volume in the first, second, and third 24h periods after injury in the PiCCO monitoring group was significantly higher than that in the conventional monitoring group (t=-3.120, -2.448, -2.694, P=0.004, 0.020, 0.011), but there was no statistically significant difference in urine output (t=0.258, -0.748, -1.023, P=0.798, 0.460, 0.315), as shown in Table 2. The fluid replacement coefficients in the first and second 24h periods in the PiCCO monitoring group were higher than those in the conventional monitoring group (t1=-2.263, -2.149, P1=0.031, 0.040). The fluid replacement coefficient in the first 24- h period in the conventional monitoring group was close to the planned value (t2=0.947, P2=0.358), and it was significantly higher than the planned value in the second 24h period (t2=3.016, P2=0.008). The fluid replacement coefficients in the first and second 24h periods in the PiCCO monitoring group were significantly higher than the planned values (t3=4.019, 4.542, P3 both<0.001). There was no statistically significant difference in urine output per hour per kilogram of body weight between the two groups in the first and second 24h periods (t1=-0.307, -1.115, P1=0.761, 0.274), but it was significantly higher than the planned value in both groups (in the conventional group, t2=2.758, 4.646, P2=0.014<0.001; in the PiCCO group, t3=5.618, 6.064, P3 both<0.001), as shown in Table 3.

Vital sign indicators

At 24h and 48h after injury, there were no statistically significant differences in the levels of MAP, CVP, and HR between the two groups (P>0. 05). At 72h after injury, the MAP and CVP in the PiCCO monitoring group were higher than those in the conventional monitoring group, and the HR was lower than that in the conventional monitoring group, with statistically significant differences (P<0. 05). See Table 4.

Key resuscitation indicators and organ function indicators

There were no statistically significant differences in the levels of Lac and BE between the two groups upon admission (P>0.05). After resuscitation (72 hours after admission), the level of Lac in the PiCCO monitoring group was significantly lower than that in the conventional monitoring group (P<0.001), and the level of BE was significantly higher than that in the conventional monitoring group (P<0.05). See Table 5. There was no statistically significant difference in the level of BUN between the two groups upon admission (P>0.05). After resuscitation (72 hours after admission), the level of BUN in the PiCCO monitoring group was significantly lower than that in the conventional monitoring group (P<0.05). There were no statistically significant differences in the levels of CK, CK - MB, ALT, AST, and Scr between the two groups upon admission and after resuscitation (72 hours after admission) (P>0.05). See Table 6.

Table 3. Comparison of fluid resuscitation coefficients ($\overline{X}\pm s$, $mL\cdot kg^{-1}\cdot \%TBSA^{-1}$) and urine output per kilogram of body weight per hour ($\overline{X}\pm s$, ml/(kg·h) at various time points post-injury between the two groups of severely burned patients.

Group	Number of Cases	Fluid replacement coefficient ($mL\cdot kg^{-1}\cdot$%TBSA-1)		Urine output per hour per kilogram of body weight (ml/(kg·h))	
		1st 24 h	2nd 24 h	1st 24 h	2nd 24 h
Conventional Monitoring Group	17	1.59±0.38	0.93±0.25	1.31±0.46	2.07±0.89
PiCCO Monitoring Group	15	1.89±0.37	1.17±0.36	1.35±0.24	2.42±0.91
t1 value	-	-2.263	-2.149	-0.307	-1.115
P1 value	-	0.031	0.040	0.761	0.274
t2 value	-	0.947	3.016	2.758	4.646
P2 value	-	0.358	0.008	0.014	<0.001
t3 value	-	4.019	4.542	5.618	6.064
P3 value	-	0.001	<0.001	<0.001	<0.001

Note: PiCCO stands for Pulse Contour Cardiac Output, and TBSA stands for Total Body Surface Area. The fluid replacement plan values of the Third Military Medical University for the fluid replacement coefficients in the first and second 24-hour periods are 1.50 and 0.75 $mL\cdot kg^{-1}\cdot \%TBSA^{-1}$ respectively. The fluid replacement plan values of the Third Military Medical University for the urine output per hour per kilogram of body weight in the first and second 24-hour periods are both 1.00 mL. The t1 values and P1 values are obtained by comparing each index of the PiCCO monitoring group with that of the conventional monitoring group at each time point. The t2 values, P2 values, t3 values, and P3 values are obtained by comparing each index of the conventional monitoring group and the PiCCO monitoring group with the planned values at each time point respectively.

Hemodynamic indicators

In the PiCCO monitoring group, the CI, CO, SVRI, EVLWI, GEDVI, and ITBVI of patients showed obvious changing trends over time after injury, and these changes were statistically significant($P<0.05$). Multiple hemodynamic indices of patients in the PiCCO monitoring group showed specific changing trends after injury. The GEDVI was lower than normal at 24 h after injury, then gradually increased, and returned to normal at 48 h and 72 h. The ITBVI was lower than normal at 24 h and 48 h after injury, then gradually increased, and reached the normal level at 72 h. The CI was lower than normal at 24 h after injury, then gradually increased, and returned to normal at 48 h and 72 h. The SVRI was higher than normal at 24 h after injury, then gradually decreased, and returned to normal at 48 h and 72 h. The CO continuously increased after injury, and the average values at the three time points were all within the normal range. The EVLWI increased at 24 h and 48 h after injury and decreased at 72 h, and the mean values at each time point did not exceed 10 mL/kg. See Table 7.

Table 4. Comparison of MAP ($\bar{X}\pm s$, mmHg), CVP ($\bar{X}\pm s$, mmHg), and HR ($\bar{X}\pm s$, beats/min) levels at various time points post-injury between the two groups of severely burned patients.

Group	Number of Cases	MAP (mmHg) at 24 hours after injury	MAP (mmHg) at 48 hours after injury	MAP (mmHg) at 72 hours after injury	CVP (mmHg) at 24 hours after injury	CVP (mmHg) at 48 hours after injury	CVP (mmHg) at 72 hours after injury	HR (beats/min) at 24 hours after injury)	HR (beats/min) at 48 hours after injury	HR (beats/min) at 72 hours after injury
Conventi-onal Monitoring Group	17	77.55 ±6.30	86.10 ±8.57	92.77 ±8.02	8.11 ±3.33	8.15 ±3.20	9.24 ±3.07	119.65 ±8.90	113.06 ±7.47	110.24 ±9.32
PiCCO Monitoring Group	15	79.91 ±9.25	88.53 ±7.86	99.94 ±4.88	6.53 ±2.47	8.87 ±3.18	11.4 ±2.73	124.73 ±10.05	113.00 ±5.13	103.20 ±6.89
T value	-	-0.856	-0.835	-3.005	1.512	-0.637	-2.097	-1.518	0.026	2.399
P value	-	0.399	0.410	0.005	0.141	0.529	0.044	0.139	0.980	0.023

Note: PiCCO stands for Pulse Contour Cardiac Output. 1 mmHg = 0.133 kPa. The range of mean arterial pressure (MAP) is 70-105 mmHg; the range of central venous pressure (CVP) is 8-12 mmHg; the range of heart rate (HR) is 60-100 beats/min.

Table 5. Comparison of the levels of Lac (($\bar{X}\pm s$, mmol/L) and BE (($\bar{X}\pm s$, mmol/L) between the two groups of patients with extremely severe burns upon admission and after resuscitation (72 hours after admission).

Group	Number of Cases	Lac at Admission (mmol/L)	Lac after Resuscitation (mmol/L)	BE at Admission (mmol/L)	BE after Resuscitation (mmol/L)
Conventional Monitoring Group	17	4.95±2.05	2.79±0.86	-5.52(-7.10, -3.21)	-1.60(-2.94, 0.25)
PiCCO Monitoring Group	15	5.05±2.32	1.62±0.54	-5.00(-7.00, -2.50)	1.50(-1.30, 4.50)
T value / Z value	-	-0.121	4.533	-0.567	-2.476
P value	-	0.904	<0.001	0.571	0.013

Note: PiCCO stands for Pulse Contour Cardiac Output. Lac stands for blood lactate, and BE stands for base excess.

Table 6. Comparison of the Levels of CK and CK - MB, ALT and AST, BUN and Scr between the two groups of severely burned patients upon admission and after resuscitation (72 hours after admission).

Group	Number of Cases	CK at Admission (U/L)	CK after Resuscitation (U/L)	CK - MB at Admission (U/L)	CK - MB after Resuscitation (U/L)	ALT at Admission (U/L)	ALT after Resuscitation (U/L)	AST at Admission (U/L)	AST after Resuscitation (U/L)	BUN at Admission (mmol/L)	BUN after Resuscitation (mmol/L)	Scr at Admission (μmol/L)	Scr after Resuscitation (μmol/L)
Conventional Monitoring Group	17	265.60 (118.00, 669.50)	130.00 (87.50, 468.00)	77.00(51.50, 145.00)	38.00 (21.00, 54.00)	38.00 (25.50, 65.50)	16.00 (13.00, 21.50)	72.00 (55.50, 92.00)	19.00 (17.00, 24.50)	8.13 ±1.45	5.79 ±1.87	91.75±17.79	68.36±12.45
PiCCO Monitoring Group	15	1166.00 (208.70, 18761.00)	532.00 (145.70, 4835.00)	110.00 (64.10,140.00)	49.00 (28.00, 88.00)	28.00 (21.00, 49.00)	19.00 (16.00, 51.00)	72.20 (55.00, 280.00)	19.30 (19.00, 126.00)	8.07 ±3.35	4.55 ±0.77	114.14 ±47.34	63.18±13.82
T value /Z value	-	-1.454	-1.605	-0.548	-0.737	-1.171	-1.684	-0.718	-1.805	0.067	2.508	-1.727	1.116
P value	-	0.146	0.108	0.584	0.461	0.242	0.092	0.473	0.071	0.947	0.020	0.102	0.273

Note: PiCCO stands for Pulse Contour Cardiac Output; CK stands for Creatine Kinase, and CK - MB stands for Creatine Kinase - MB Isoenzyme (Myocardial Type); ALT stands for Alanine Aminotransferase; AST stands for Aspartate Aminotransferase; Scr stands for Serum Creatinine, and BUN stands for Blood Urea Nitrogen.

Table 7. Comparison of hemodynamic indicators at various time points post-injury in the PiCCO monitoring group ($\overline{X}$±s)

Time	Number of Cases	CI(L/min/m2)	CO(L/min)	EVLWI(ml/kg)	SVRI/ (dyn·s·m^2/cm^5)	GEDVI (mL/m^2)	ITBVI (mL/m^2)
24 h after Injury	15	2.62±0.72	4.48±1.07	6.0±1.6	2415.19 ±515.07	653±109	786±137
48 h after Injury	15	3.60±0.71	6.16±1.06	7.6±1.1	1821.34 ±344.62	688±102	831±128
72 h after Injury	15	4.54±1.06	7.77±1.63	6.9±1.5	1705.53 ±315.07	747±140	904±175
F value	-	56.615	55.075	6.901	28.759	13.210	15.387
P value	-	<0.001	<0.001	0.004	<0.001	0.001	<0.001

Note: PiCCO represents Pulse Contour Cardiac Output. The normal value of Global End-Diastolic Volume Index (GEDVI) is 680-800 mL/m², the normal value of Intrathoracic Blood Volume Index (ITBVI) is 850-1000 mL/m², the normal value of Cardiac Index (CI) is 3-5 L·min^{-1}·m^{-2}, the normal range of Cardiac Output (CO) is 4-8 L/min, the normal value of Extravascular Lung Water Index (EVLWI) is 3.0-7.0 mL/kg, and the normal value of Systemic Vascular Resistance Index (SVRI) is 1700-2400 dyn·s·cm^{-5}·m^2.

Prognosis - related indicators

There were no statistically significant differences in the complications, 30-day mortality, number of days of antibiotic use, length of hospital stay, and hospitalization expenses between the two groups of patients ($P > 0.05$). See Table 8.

Discussion

Early treatment of extremely severe burns hinges on swiftly restoring the effective circulating blood volume during the shock phase and enhancing microcirculation and oxygen delivery. As burn area enlarges and depth deepens, fluid replacement requirements surge [26]. Proactive prevention and treatment of early burn shock are pivotal for successful outcomes. Currently, the "timely, rapid, and sufficient" principle should be adhered to in early burn fluid resuscitation. Nevertheless, accurately controlling the fluid replacement volume via traditional formulas remains challenging. Clinically, reliable hemodynamic evaluation metrics are urgently needed for precise fluid resuscitation. Given the complex pathophysiology and unstable hemodynamics of patients with extremely severe burns, establishing a dependable monitoring system is of great significance. Non-invasive monitoring is user-friendly but prone to interference, while invasive monitoring offers precise parameters at the cost of complex operations, high costs, and potential complications[27, 28].

In recent years, the PiCCO monitoring technology has emerged as a minimally invasive approach with remarkable advantages. By integrating the transpulmonary thermodilution method and arterial pulse contour analysis, it enables continuous and dynamic hemodynamic monitoring, providing parameters such as cardiac output and EVLWI. It is easy to operate and has few complications [29, 30]. PiCCO has enhanced hemodynamic stability and reduced the incidence of Multiple Organ Dysfunction Syndrome(MODS) in sepsis patients. However, its benefits in extremely severe burn patients are yet to be fully validated. Early provision of accurate hemodynamic data can assist clinicians in refining treatment plans.

Blood lactate and base excess are vital for assessing shock and resuscitation, as they can sensitively reflect tissue hypoperfusion and changes in effective circulating blood volume [31]. The initial 24 hours post-burn is the "golden window" for fluid resuscitation [32]. This study compared the PiCCO and conventional monitoring groups and found that in the first 3 post - injury 24 - hour periods, the total fluid replacement volume in the PiCCO group was significantly higher. The difference in the fluid replacement coefficient was more pronounced in the first 2 24-hour periods. Both groups presented with ischemia and hypoxia upon admission. After 72-hour fluid resuscitation, blood lactate and base excess values improved in both groups, with more significant improvements in the PiCCO group. This could be because traditional - indicator - guided resuscitation may lead to insufficient fluid replacement, while PiCCO can accurately assess volume status and offers more advantages in managing early shock correction in extremely severe burns. The study also found that the fluid replacement coefficient in the PiCCO group exceeded the standard protocol value in the first 2 24-hour periods, and the conventional group also surpassed it in the second 24-hour period. This might be due to the current protocol's failure to fully account for burn depth. Since deep burns demand more fluid, and the standard value is a theoretical estimate with large individual variations, clinically, multiple factors should be considered, and individualized resuscitation strategies should be combined with dynamic monitoring[26, 33]. Multiple studies have shown that shock patients often require more fluid than calculated by traditional formulas, and this study indicates that the PiCCO group better meets the needs of extremely severe burn patients.

Table 8. Comparison of complications, 30-day mortality, days of antibiotic use, length of hospital stay, and hospitalization costs between the two groups of patients with extremely severe burns.

Group	Number of Cases	Complications		30-day Mortality		Antibiotic Use Duration (days)	Hospita-lization Duration (days)	Hospitalization Expenses (10,000 yuan)
		Only Hypovolemic Shock	Including Other Complications	Yes	No			
Conventional Monitoring Group	17	12	5	1	16	42(30, 58)	54(33, 73)	56.70(30.10, 73.05)
PiCCO Monitoring Group	15	8	7	3	12	47(6, 70)	47(6, 72)	71.10(39.90, 126.80)
Z value	-	-		-		-0.132	-0.434	-1.152
P value	-	0.467*		0.319*		0.895	0.664	0.249

Note: PiCCO represents Pulse Contour Cardiac Output; * indicates the Chi-square test; "—" indicates that there is no value for this statistic.

Urine output, a traditional shock resuscitation indicator, can reflect renal perfusion and systemic circulation. However, normal absolute urine output does not rule out tissue hypoperfusion. Using urine output per kilogram of body weight per hour as a standardized parameter can more sensitively evaluate tissue perfusion and is a more reliable resuscitation endpoint indicator. In the first 2 24-hour periods, this indicator was higher than the protocol value in both groups, possibly due to diuretic use. In the second 24-hour period, the PiCCO group had a slightly higher value, suggesting its advantage in shock improvement.

Hemodynamic indicators are crucial for evaluating patient condition and resuscitation efficacy. At 24 and 48 hours post-injury, the two monitoring methods had similar hemodynamic effects. However, at 72 hours, the PiCCO group had significantly higher mean arterial pressure (MAP) and central venous pressure (CVP) and a significantly lower heart rate (HR), indicating its potential in fluid resuscitation to ensure blood flow stability and enhance cardiac function.

Extremely severe burns can damage the myocardium, kidneys, and liver. The sudden drop in effective circulating blood volume activates the Renin - Angiotensin - Aldosterone System (RAAS), leading to the "shock heart", i.e., the heart may experience accelerated heart rate, altered myocardial contractility, and decreased cardiac output, accompanied by cardiomyocyte ischemia and hypoxia, impaired energy metabolism, and even cardiomyocyte damage, apoptosis, and impaired cardiac function. A state of the heart in which the function and structure of the heart are abnormally altered in a state of shock. Thus, myocardial protection should be emphasized during early shock fluid resuscitation [34]. A moderate increase in heart rate can improve coronary perfusion, while excessive increases can worsen myocardial damage. The study showed that at 72 hours post-injury, the PiCCO group had a lower and more rapidly decreasing heart rate ($p < 0.05$), which was beneficial for cardiac function, possibly due to individualized fluid management and myocardial protection drugs. There was no significant difference in traditional myocardial injury indicators like CK - MB between the two groups ($p > 0.05$), possibly due to their lack of specificity [35]. Renal function impairment is a common and serious complication, and preventing acute kidney injury is crucial. After severe burns, factors such as fluid loss and RAAS activation exacerbate renal insufficiency [36, 37]. Timely fluid resuscitation is the key. Abnormal increases in blood urea nitrogen and serum creatinine can diagnose AKI [38, 39]. There was no significant difference in these indicators between the two groups upon admission ($P > 0.05$), and they normalized after 72-hour resuscitation. The PiCCO group had lower blood urea nitrogen ($P < 0.05$), suggesting that PiCCO can precisely guide resuscitation and improve renal perfusion and function. Extremely severe burns can damage liver cells, causing elevated liver enzymes. In this study, there was no significant difference in ALT and AST levels between the PiCCO and conventional groups upon admission and 72 hours after resuscitation ($P > 0.05$), indicating similar liver function protection effects. Liver injury is mainly influenced by burn severity and systemic inflammation, and ALT/AST is insensitive to early-stage resuscitation strategies.

The PiCCO group initially exhibited "low cardiac output and high peripheral resistance" shock characteristics. The cardiac index (CI) was below normal at 24 hours post-injury and gradually recovered after 48 hours. The systemic vascular resistance index (SVRI) was above normal at 24 hours and decreased after 48 hours. The global end-diastolic volume index reflects the recovery of effective circulating blood volume. The extravascular lung water index increased at 48 and 72 hours post-injury, suggesting possible excessive fluid replacement in the second 24-hour period. Its decrease from 48 to 72 hours indicates recovering pulmonary vascular endothelial barrier function, necessitating optimization of the fluid replacement strategy. Based on this, comprehensive treatment during the shock period should include using positive inotropic drugs for myocardial contraction dysfunction and appropriate vasodilators. During the absorption - return period, vasoactive drugs should be used rationally, diuresis enhanced, and fluid input controlled. The PiCCO monitoring system provides valuable references for individualized treatment.

Prognosis-related indexes showed that the differences in complication rates and mortality rates between the two groups were not statistically significant. In conclusion, this study has the limitation of a small sample size, and at the same time, as a retrospective study, it is difficult to completely avoid bias. In addition, potential confounding factors such as patients' comorbidities may have affected the results of this study to different degrees. In future studies, we will consider enlarging the sample size and extending the follow-up period, conducting prospective studies, and strengthening the control and analysis of potential confounders to more accurately assess the clinical value of PiCCO monitoring in the treatment of patients with very severe burns.

Conclusion

This study compared PiCCO and conventional monitoring in extremely severe burn fluid resuscitation and confirmed the PiCCO group's advantages in improving tissue perfusion and organ function protection. PiCCO provides precise data for formulating individualized fluid resuscitation strategies by continuously monitoring key parameters such as CI and GEDVI. Although there were no significant differences in endpoint indicators like complication incidence and mortality, PiCCO significantly optimized the resuscitation process. Based on current evidence, PiCCO monitoring is recommended for patients with extremely severe burns and unstable hemodynamics. Future multi-center large-sample studies are needed to further validate its clinical value in improving long-term patient prognosis.

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Author Contributions

Lulu Jiang: Writing – original draft, Writing–review & editing, Visualization, Conceptualization, Formal analysis, Software, Methodology, Investigation. Yindong Wu: Data curation, Validation. Zijian Zhang: Project administration, Resources. Youxin Yu: Project administration, Resources. Yi Hu: Supervision. Delin Hu: Supervision.

Ethics approval and consent to participate

All data used in this study were analyzed in accordance with ethical guidelines and regulations.

Competing Interests

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.

Data Availability

The data generated or analyzed in this study are available from the corresponding authors upon reasonable request.

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