Association of intraoperative blood gas analysis with patient outcome after adult cardiac surgery

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Research article

Keywords: Blood gas analysis, Postoperative outcomes, Optimal pH, Cardiac surgery

Posted Date: June 17th, 2019

DOI: https://doi.org/10.21203/rs.2.1748/v2

Abstract

Background: The associations of the different blood gas parameters from different blood samples harvested at different stages during adult cardiac surgery with the postoperative outcomes are inadequately studied. Methods: Adult patients undergoing elective cardiac surgery with cardiopulmonary bypass (CPB) participated in this prospective observational study. Blood gas parameters from arterial, central venous, and jugular bulb venous blood samples harvested simultaneously at pre-determined time points (baseline with the patient awake, post-anesthesia induction but before CPB, during CPB at 30°C, during CPB at 37°C (rewarming), and at the end of surgery) were correlated with postoperative outcomes including the length of mechanical ventilation (LMV), intensive care unit stay (LICU), hospital stay (LOH), and major organ morbidity and mortality. Results: Data from 193 patients were analyzed. Multiple parameters of different blood harvested at different stages significantly correlated with one or more outcome measures based on univariate analysis ($p < 0.05$). However, only the jugular bulb venous blood pH and carbon dioxide tension and the central venous blood pH at the end of surgery (pHcv-end) were significantly correlated with LMV, LICU, and LOH ($p < 0.05$). A more alkaline blood correlated with more favorable outcomes. After adjusting for age, surgical time, and total intravenous volume administered, multivariate analysis showed that only pHcv-end remained independently associated with LMV and LICU ($p < 0.05$). Conclusion: More alkaline blood, especially the central venous blood at the end of surgery, is associated with more favorable outcomes after adult cardiac surgery. Trial registration ChiCTR-POC-17013942, Date of registration December 15, 2017.

Background

Open cardiac surgery is one of the definitive therapeutic option for certain cardiovascular lesions based on efficacy and survival data.[1, 2] However, it is associated with a high incidence of various complications, including atrial fibrillation (19%),[3] acute kidney injury (~20%),[4] cerebral injury (>50%),[5] postoperative delirium (12.5–22%),[6] ischemic stroke (1.2%),[7] myocardial infarction (4.8%),[8] and death (2.7%)[9]. Multiple factors, relevant to patients,[10] surgery,[11] anesthesia,[12] and cardiopulmonary bypass (CPB),[13] have been linked to the unfavorable outcomes after cardiac surgery. For intraoperative care, the factors that can be modified during surgery and are outcome-relevant should be identified and optimally managed. Blood gas analysis is routinely performed during cardiac surgery. Most blood gas parameters include pH, oxygen tension (PO_2), oxygen saturation (SO_2), carbon dioxide tension (PCO_2), and even lactate, can be modified during surgery. The associations of different blood gas parameters , such as central venous blood oxygen saturation,[14] mixed venous blood oxygen saturation,[15] central venous to arterial blood PCO_2 difference,[16] and lactate[17, 18] with patient outcomes after cardiac surgery have been shown. Compared with the pH-stat, the alpha-stat blood gas management leads to improve neuropsychologic outcomes in adult patients undergoing moderate hypothermic CPB.[19, 20] However, the correlations of the different parameters included in blood gas analysis from different blood samples (arterial vs. jugular bulb venous vs. central venous) harvested at different stages of cardiac surgery with postoperative outcomes have not been specifically studied.

We hypothesized that different blood gas parameters based on arterial, jugular bulb venous, and central venous blood samples harvested at different time points during cardiac surgery have different associations with postoperative outcomes. One of the aims of this prospective observational study is to explore if there is an optimal pH band within the normal pH range of blood gas analysis that is associated with more favorable outcomes after adult cardiac surgery.

Methods

This was a prospective observational cohort study. The study was approved by the Institutional Review Board of Guizhou Provincial People's Hospital (#2014099). Verbal and written informed consents were obtained from all participants before surgery.

Patients

Patients who met the following inclusion criteria from December 20, 2017, to December 30, 2018, were recruited for this study: 1) age ≥ 18 years, 2) elective cardiac surgery, and 3) CPB requirement. We excluded patients younger than 18 years or scheduled for surgeries that were emergent, off-pump, or that required deep hypothermic circulatory arrest.

Vascular cannulation

Before anesthesia induction, the following vascular cannulations were performed under local anesthesia. A 20G catheter was inserted into a radial artery for beat-to-beat arterial blood pressure monitoring and blood sampling. A 20-cm-long 7F triple lumen central venous catheter was inserted into the superior vena cava for central venous pressure monitoring and blood sampling. A 20-cm-long 16G single lumen catheter was inserted retrogradely into the right internal jugular vein until encountering resistance, and it was then slowly retracted until the blood was aspirated for jugular bulb blood sampling.[21] The position of the catheter for jugular bulb blood sampling was confirmed by fluoroscopy.

Anesthetic care

Anxiolytics were given to patients at the discretion of anesthesiologists before surgery. In the operating room, patients were monitored using electrocardiography, pulse oximetry, and invasive arterial blood pressure. Following pre-oxygenation, anesthesia was induced with midazolam (0.1 mg/kg), etomidate (0.2–0.5 mg/kg) or propofol (1–2 mg/kg), and sufentanil (0.2–0.5 mcg/kg). Endotracheal intubation was facilitated by muscle relaxation using vecuronium (0.1 mg/kg). Anesthesia was maintained using sevoflurane, with intermittent boluses of sufentanil for analgesia and vecuronium for muscle relaxation. Patients were mechanically ventilated with a tidal volume of 6–8 ml/kg, a respiratory rate of 8–12 times per minute, and an inspired oxygen fraction of ~70%. A nasopharyngeal probe was used for temperature monitoring.

Surgery and CPB

Surgery was performed through midline sternotomy. Heparin was administered to maintain an activated clotting time > 480 seconds. Non-pulsatile CPB with a membrane oxygenator was used. The temperature during CPB was maintained at 30°C. Patients were rewarmed to a target nasopharyngeal temperature of 37°C before the termination of CPB. The target mean arterial pressure during CPB was 60-80 mmHg. Inotropic and vasopressor options included dobutamine, epinephrine, and norepinephrine, which were given as intravenous infusions alone or in combination as needed.

Blood gas analysis

Arterial, jugular bulb venous, and central venous blood gases were analyzed (GEM premier 3000, Instrumentation Laboratory, Bedford, MA, USA) using blood samples harvested from the radial artery, jugular bulb, and central vein, respectively. Blood samples were harvested at the following time points: 1) before anesthesia induction (pre), 2) after anesthesia induction (post), 3) CPB with body temperature at ~30°C (30°C), 4) during CPB with the patient rewarmed to ~37°C (37°C), and 5) at the end of surgery (end).

Patient outcomes

The primary outcome measures included lengths of mechanical ventilation (LMV), intensive care unit stay (LICU), and hospital stay (LOH). The secondary outcome measure was the incidence of major organ morbidity and mortality (MOMM) defined by the Society of Thoracic Surgeons.[22] MOMM is a composite measure of any of the following occurrences: 1) operative mortality defined as death from any cause; 2) stroke defined as a new-onset central nervous system deficit persisting longer than 72 hours; 3) renal failure defined as a new requirement for dialysis or an increase in serum creatinine to more than 2.0 mg/dl and double the most recent preoperative measurement; 4) prolonged ventilation defined as a need for mechanical ventilation longer than 24 hours; 5) deep sternal wound infection; and 6) reoperation for any reason.

Data collection

Patients' demographic data including age, gender, weight, New York Heart Association (NYHA) classification, and American Society of Anesthesiologists (ASA) physical status scores were collected. We also obtained data on comorbidities including diabetes, dyslipidemia, hypertension, stroke, and myocardial infarction. And, we collected data including preoperative ejection fraction, medications (angiotensin converting enzyme inhibitors, beta-blockers, nitroglycerin, digoxin, and diuretics), procedural details (CPB time, aortic cross-clamp time, surgical time, and type of surgery), and anesthetic details (agents and drugs used, blood products and fluid administered). The results of blood gas analysis of different types (arterial, jugular bulb, and central venous blood) at different pre-determined time points were recorded. Postoperative outcomes including LMV, LICU, LOH, and MOMM were prospectively collected. All patients were followed up with medical records were reviewed on a daily basis until discharge.

Statistical analysis

In a multiple linear regression analysis of a continuous dependent outcome, a sample size of 190 achieves 80% power to detect an R^2 of 0.03 attributed to 1 independent variable (i.e., a blood gas parameter) when using an F-test with a significance level (alpha) of 0.05 and adjusting for an additional 5 independent variables (covariates) with an R^2 of 0.20 (0.4). The value of R^2 = 0.03 is equivalent to a global Cohen's f^2 effect size of 0.03 (= $R^2/(1- R^2)$), and f^2 values of 0.02, 0.15, and 0.35 represent small, medium, and large effect sizes, respectively.

Continuous variables were checked for normality of the distribution. If normally distributed, data were presented as the mean ± SD. Otherwise, medians [interquartile range] was reported. Categorical variables were expressed as actual numbers and percentages.

Three outcomes (LMV, LICU, and LOH) were log-transformed before the linear regression analyses. A simple (i.e., univariate) regression analysis was performed first to look for the association of a single factor (e.g., patient demographics, blood gas parameters, and other clinical covariates) with each the dependent outcome (i.e., LMV, LICU, and LOH), separately. To avoid fitting too many models, only those factors that were found significantly (i.e., $p < 0.05$) associated with all three outcomes were entered in the multiple linear regression analysis to identify independent risk factors. Because we aimed to assess the association of a blood gas parameter with the outcome after adjusting for important covariates, if one of the blood gas parameters was found to be statistically significant in the univariate analysis, we always kept it in the multivariable model, in which a backward selection procedure was implemented to select for other risk factors, with an entry and exit significance level of 0.10. Collinearity between factors was determined by variance inflation factors (< 10). The regression coefficient (beta) and its standard error were reported to quantify the effect sizes for the final factors that remained in the multiple regression model.

Next, we dichotomized LMV, LICU, or LOH into binary outcomes (unfavorable, for values > median; favorable, for values ≤ median). Comparisons of patient demographics, blood gas parameters, and other clinical covariates between two groups stratified by three new binary outcomes and MOMM were performed by univariate logistic regression analyses. As a measure of effect size, the odds ratio (OR) was calculated with a 95% confidence interval (CI) for each factor.

All statistical analyses were performed using the IBM SPSS 23.0 package (Chicago, IL, USA) and the SAS software version 9.4 (Cary, NC, USA). A two-sided p-values lower than 0.05 was considered to be statistically significant.

Results

A total of 203 patients participated in this study. We excluded 10 patients as a result of missing arterial (n = 4) or jugular bulb (n = 6) blood gas data. The demographic and clinical profiles of the study population are summarized in Table 1. The average age of the 193 patients was 48 ± 10 years, and 69 (35.8%) of them were male. All 193 patients had arterial and jugular bulb blood gas data at the five pre-determined time points, with 126 patients also having complete central venous blood gas data. Postoperatively, 26

(13.5%) patients developed MOMM; among these, 7 (3.6%) died during hospitalization. The median (IQR) of LMV, LICU, and LOH were 510 [360–890] minutes, 1200 [1060–1300] minutes, and 14 [11-16] days, respectively. The data of perioperative blood gas parameters are summarized in Table 2.

The clinical factors and blood gas parameters that were found to be statistically associated with any of the primary outcomes are presented in the Supplemental Table 1. Notably, the pH of jugular bulb venous and central venous blood samples at the end of surgery (pHjv-end and pHcv-end) and the jugular bulb blood carbon dioxide tension at the end of surgery ($PjvCO_2$-end) were significantly correlated with all outcome measures including LMV ($p < 0.001$), LICU ($p < 0.001$), and LOH ($p < 0.05$).

The clinical covariates that significantly correlated with all primary outcomes (LMV, LICU, and LOH) in the univariate analysis included age, CPB time, surgical time, fresh frozen plasma, and total input volume. Given that CPB and surgical time were highly correlated with each other ($r = 0.79$, $p < 0.001$), we only included surgical time in the multiple regression analysis based on the consideration of collinearity. In addition, since fresh frozen plasma was only given to 23 (11.9%) patients, we dropped it from the multiple variable model. The results of the final multiple regression models are shown in the Table 3. After adjusting for age, surgical time, and total input volume, pHcv-end was significantly associated with LMV (beta (S.E.) = −0.856 (0.408), $p = 0.038$) and LICU (beta (S.E.) = −0.787 (0.267), $p = 0.004$), but pHjv-end and $PjvCO_2$-end were no more significantly associated with the outcomes.

The factors that were found to be statistically associated with any of the four binary outcomes are presented in the Supplemental Table 2. Age was found to increase the odds of unfavorable outcomes for LMV (OR, 1.05; 95% CI, 1.01–1.08; $p = 0.004$), LOH (OR, 1.02; 95% CI, 1.00–1.06); $p = 0.043$), and MOMM (OR, 1.07; 95% CI, 1.02-1.12; $p = 0.009$). Among the blood gas parameters, a higher arterial blood pH at the end of surgery was found to significantly decrease the odds for unfavorable outcomes for LMV (OR, 0.94; 95% CI, 0.89–0.99; $p = 0.024$) and LICU (OR, 0.94; 95% CI, 0.89–0.99; $p = 0.019$). Statistically significant associations with LMV and LICU were also found for blood gas parameters of pHjv-end, pHcv-end, and $PjvCO_2$-end. In addition, pHcv-end was significantly associated with MOMM (OR, 0.92; 95% CI, 0.84–1.00; $p = 0.041$).

The variation trends of blood gas at different stages in different groups which dichotomized LMV, LICU, or LOH into binary outcomes (favorable, for values ≤ median; unfavorable, for values > median) and MOMM(without or with) are presented in Supplemental Table 3,4,5,6. The pH of arterial and jugular bulb venous blood samples at the end of surgery (pHa-end, pH jv-end) in the LMV ≤510 minutes and LICU ≤1200 minutes groups are higher than that of the LMV>510 minutes (arterial:7.429±0.052 vs 7.409±0.058, P=0.018; jugular bulb venous:7.359±0.043 vs 7.345±0.047, P=0.026) and LICU>1200(arterial: 7.429±0.050 vs 7.409±0.061, P=0.022; jugular bulb venous: 7.359±0.041 vs 7.343±0.048, P=0.035) groups. The pH of central venous blood samples(pHcv-end) at the end of surgery in the LMV≤510miutes , LICU≤1200mintues and without MOMM groups are higher than that of LMV>510 minutes(7.382±0.052 vs 7.361±0.057, P=0.029), LICU>1200minutes (7.387±0.050 vs 7.350±0.056, P<0.001) and with MOMM (7.373±0.055 vs 7.346±0.057, P=0.038) groups. As shown in the line charts that depict the associations

among pHa-end, pHjv-end, pHcv-end, and different outcome measures (Figure 1,2,3,4), a higher pH or more alkaline arterial and jugular bulb venous blood was associated with a shorter LMV and LICU, as well as a higher central venous blood at the end of surgery was associated with more favorable outcomes (i.e., a shorter LMV and LICU, less MOMM).

Discussion

Our study demonstrated that multiple blood gas parameters based on different blood samples harvested at different time points during cardiac surgery are significantly associated with postoperative outcomes. The pH value of the central venous blood at the end of surgery has a consistent correlation with different outcomes measured in this study. More alkaline blood is associated with more favorable outcomes, suggesting that there may be an optimal band within the normal range of blood gas analysis that is associated with more favorable outcomes after adult cardiac surgery with CPB.

The correlations between pH and outcomes have been previously investigated in patients undergoing cardiac surgery. In elderly cardiac surgical patients (≥ 75 years old), it was found that the arterial blood pH measured after surgery and on admission to the ICU was significantly higher in patients without than with postoperative complications(7.43 vs. 7.41) and in survivors than non-survivors (7.42 vs 7.35).[23] In adult cardiac surgical patients, several randomized controlled trials showed that alpha-stat management, the strategy of maintaining more alkaline blood during moderate hypothermia, is associated with more favorable neurologic and cognitive outcomes than the alternative pH-stat management.[19, 20, 24] Since the aim of alpha-stat is to keep a nontemperature corrected pH of 7.4 and a PCO_2 of 40 mmHg irrespective of a patient's actual body temperature, this technique conserves the ionization of the imidazole groups on intracellular proteins and maintain intracellular electrochemical neutrality, buffering, and enzymatic function.[25] It might be expected to preserve enzyme function, protein structure and function, net membrane charge, transport characteristics,[26] thereby contributing to the protection of organ function. The standard normal pH ranges from 7.35 to 7.45 and values outside of this range are considered abnormal. However, both our study and previous studies[23] showed that although the pH value is within the normal range, a higher pH value(i.e., a more alkaline blood) is associated with more favorable outcomes compared with a lower pH value (i.e., a more acidic blood) in elective adult cardiac surgery. It is thus suggested that there may be a narrow optimal band within the normal pH range that is associated with more favorable outcomes.

Partial pressure of carbon dioxide is another important acid-base parameter in our study. The results of univariate analysis showed that a higher arterial , central venous and jugular venous PCO_2 values have a significant positive correlation with longer duration of LMV and LICU. The pH alteration is used to accomplish PCO_2 change, as the PCO_2 increases the pH decreases , therefore, the results of the correlation between PCO_2 and outcomes is consistent with that of pH. Meanwhile , a increased arterial and venous PCO_2 indicate a increased production and a reduced clearance of CO_2 which indirectly suggest that the patient may experience occult tissue hypoperfusion with less of pH value and higher PCO_2, thus caused the mechanical ventilation time and ICU stay delayed.

However, it's worth notice that PCO_2 is not an independent predictor of outcomes in our study. The pH level is determined by many factors such as bicarbonate concentration, carbon dioxide tension, volatile and non-volatile acid concentrations, as well as coexisting acid–base disorders, [27]etc. therefore, as a combination of co-regulating by a series of complex factors, pH can, on the whole, better represent the overall body situation.This theory also supports why there is a strong correlation between pH and outcomes.

Our study uniquely demonstrated that, although arterial blood is normally used for blood gas analysis in clinical care, venous blood gas may have a better prognostic value after cardiac surgery. Our study also showed that central venous blood gas has a more consistent correlation with the outcomes measured in our study than does jugular bulb blood gas. A possible explanation is that the arterial blood gas data provide an assessment of pulmonary gas exchange, whereas the central venous data represent tissue acidity and oxygenation as determined by the relation between tissue perfusion and microcirculation metabolic demands.[28] Thus , it is likely possible that central venous pH is one of the most powerful predictors of outcome in our cohort. As for the difference between the central venous blood and jugular bulb venous blood is that superior vena cava receives venous return from the upper half of the body above the diaphragm , the jugular bulb collects blood from the cerebral hemisphere which mainly represent brain condition, therefore central venous blood gas provide more systemic information than that of jugular bulb venous blood gas. Because the length of postoperative mechanical ventilation, ICU stay, hospital stay, and the incidence of MOMM events depend on overall body situation, so it can be explain mostly why central venous blood gas is more associated with prognosis than that of jugular bulb. However, the value of jugular bulb venous blood gas has been confirmed by the finding that its desaturation is associated with impaired postoperative cognitive test performance.[29] The cause of the different results between our study and this previous study may be due to the different outcomes that were assessed. In clinical practice, the decision of which blood sample to use for gas analysis should be determined based on considerations including patient population, the physiology of concern, and the outcome relevance, since the information provided by different blood gas analyses is distinctive.[30, 31]

Multiple *non-pH* blood gas parameters from different blood samples harvested at different stages of surgery also correlate with the outcomes measured in our study. Our findings are corroborated by the previous evidence showing that, in adult cardiac surgery, a higher arterial blood lactate concentration,[17, 18] a greater central venous to arterial blood PCO_2 difference,[16] a higher[14] or lower[32] central venous blood oxygen saturation, and a lower mixed venous blood oxygen saturation[15] all correlate with unfavorable outcomes. It is also intriguing to ask, although it cannot be determined by our study, what the optimal bands within the normal ranges are of these parameters associated with more favorable outcomes.

Our results also suggested that the blood gas analyzed at the end of surgery has a better association with outcomes in our patient population. Two factors might have contributed to the significance. The first was that the pH value at the end of the surgery reflects the general condition of the patient after undergoing anesthesia and surgery. The second is likely that the pH value in the observation cohort population have a

significant change at this time point. However, this finding does not indicate that blood gas analysis at earlier surgical stages is not necessary. Optimal homeostasis throughout surgery may mandate for frequent blood gas analysis at different surgical stages or whenever the clinical situation requires. Most of the blood gas parameters can be readily modified by a variety of interventions within a short period of time; therefore, blood gas may need to be checked more frequently in volatile clinical situations.

Our study has limitations. First, the cause-effect relationship between the results of blood gas parameters and postoperative outcomes cannot be determined by our exploratory cohort study, although the association between pH and outcome is likely a cause and effect relationship based on previous randomized controlled trials comparing alpha-stat and pH-stat management.[19, 20, 24]Second, as a result of the relatively small sample size, we were unable to adequately adjust for confounding variables in the regression analyses. Therefore, significant residual confounding was possible such that our results might be biased. Third, some of our reported p-values (e.g., those in the range of 0.01-0.05) would be statistically significant if the multiple tests were adjusted for in the analyses.

Conclusions

Multiple blood gas parameters from arterial, jugular bulb venous, and central venous blood harvested at different time points during cardiac surgery are associated with various postoperative outcomes in adult patients. Although the pH of the central venous blood at the end of surgery consistently correlates with the outcomes measured in this study, we cannot recommend using venous blood exclusively for gas analysis and only checking the central venous blood at the ending stage of surgery. Although more alkaline blood correlates with favorable outcomes, the optimal pH bands within the normal pH range of different blood samples during adult cardiac surgery requires further research.

Abbreviations

CPB: cardiopulmonary bypass; PO_2: blood oxygen tension; SO_2: hemoglobin oxygen saturation; PCO_2: blood carbon dioxide tension; LMV: length of mechanical ventilation; LICU: length of intensive care unit stay; LOH: length of hospital stay; MOMM: major organ morbidity and mortality; pHjv-end: the pH of jugular bulb blood at the end of surgery; pHcv-end: the pH of central venous blood at the end of surgery; PjvCO2-end: the jugular bulb blood carbon dioxide tension at the end of surgery

Declarations

Acknowledgements

We thank Xiang He, MD, Yi Ma, MD, Jing Chen, MD, Dian Feng, MD, and Ming Gao, MD from the Department of Anesthesiology, Guizhou Provincial People's Hospital, for their assistance in data collection.

Funding

This study was supported by Guizhou Provincial Science and Technology Project (#20192815 and #20161089, to KF; #20123107, to XL), and Guizhou Provincial People's Hospital Doctor Grant (#GZSYBS201505, to KF), China. It was also supported by the institutional and/or departmental sources at Yale University.

Availability of data and materials

Please contact the authors for data requests.

Authors' Contributions

KF designed the study, collected data, analysed results, and drafted the manuscript. SG and LJ designed the study, collected data, analysed results, and edited the manuscript. XL collected data and analysed results. DX collected data and analysed results. FD analysed results and edited the manuscript. LM analysed results, interpret the study, and edited the manuscript.

Ethics approval and consent to participate

The study was approved by the Ethical Committee for Clinical Research at Guizhou Provincial People's Hospital. Protocol number of the approval: 2014099. Consent to participate in the study was obtained from all patients.

Consent for publication

Obtained from all patients involved in this study.

Competing interests

The authors declare that they have no competing interests.

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Tables

Table 1. Patient demographic and clinical data (n=193). Data are expressed in mean ± SD or median [interquartile range] for continuous variables and in count (n) and percentage (%) for categorical variables.

Variables	Data
Patient characteristics	
Age (year)	48 ± 10
Male (n)	69 (35.8%)
Female (n)	124 (64.2%)
Weight (kg)	55 ± 10
ASA III (n)	127 (65.8%)
ASA IV (n)	66 (34.2%)
NYHA II (n)	11 (5.7%)
NYHA III (n)	175 (90.7%)
NYHA IV (n)	7 (3.6%)
Past medical history	
Diabetes (n)	1 (0.5%)
Dyslipidemia (n)	20 (10.4%)
Hypertension (n)	1 (0.5%)
Stroke (n)	3 (1.6%)
Myocardial infarction (n)	2 (1.0%)
Preoperative ejection fraction	
≤ 30% (n)	1 (0.5%)
30-49% (n)	18 (9.3%)
≥50% (n)	174 (90.2%)
Home medications	
ACEI (n)	24 (12.4%)
β-blockers (n)	71 (36.8%)
Digoxin (n)	141 (73.1%)
Diuretics (n)	182 (94.3%)
Procedure details	
CPB time (mins)	102 [78-126]
Aortic cross-clamp time (mins)	78 [55-98]

Surgical time (mins)	210 [180-246]
Mitral valve surgery only (n)	94 (48.7%)
Aortic valve surgery only (n)	17 (8.8%)
Mitral and aortic valve surgery (n)	78 (40.4%)
CABG and valve surgery (n)	4 (2.1%)
Anesthetic drugs	
Sufentanil (n)	193 (100%)
Dexmedetomidine (n)	138 (71.5%)
Propofol (n)	19 (9.8%)
Midazolam (n)	193 (100%)
Etomidate (n)	193 (100%)
Vecuronium (n)	193(100%)
Dobutamine (n)	186 (96.4%)
Norepinephrine (n)	58 (30.1%)
Epinephrine (n)	13 (6.7%)
Intraoperative input & output	
Red blood cell (n)	25 (13%)
Fresh frozen plasma (n)	23 (11.9%)
Total input volume (ml)	2053 [1849-2347]
Postoperative course	
Length of mechanical ventilation (mins)	510 [360-890]
Length of ICU stay (mins)	1200 [1060-1300]
Length of hospital stay (days)	14 [11-16]
In-hospital mortality (n)	7 (3.6%)
Postoperative complications	
KDIGO stage 1 (n)	24 (12.4%)
KDIGO stage 2 (n)	12 (6.2%)
KDIGO stage 3 (n)	3 (1.6%)
Renal failure requiring dialysis (n)	3 (1.6%)

Pulmonary infection (n)	11 (5.7%)
Pulmonary effusion (n)	57 (29.5%)
New onset stroke (n)	5 (2.6%)
Wound infection (n)	2 (1.0%)
Reoperation (n)	6 (3.1%)
Mechanical ventilation > 24 hours (n)	5 (2.6%)
Arrhythmia requiring treatment (n)	11 (5.7%)
Myocardial infarction (n)	0 (0%)
MOMM (n)	26 (13.5%)

ASA = American Society of Anesthesiologists; NYHA = New York Heart Association; ACEI = angiotensin converting enzyme inhibitor; CPB = cardiopulmonary bypass; CABG = coronary artery bypass grafting; ICU = intensive care unit; KDIGO = Kidney Disease Improving Global Outcomes; MOMM = major organ morbidity and mortality

Table 2:The data of perioperative blood gas parameters

Variables	Before anesthesia induction	After anesthesia induction	Cardiopulmonary bypass at 30°C	Cardiopulmonary bypass at 37°C	At the end of surgery
pHa(n=193)	7.450±0.03	7.443±0.05	7.423±0.05	7.473±0.06	7.419±0.05
pHjv(n=193)	7.374±0.02	7.355±0.04	7.351±0.04	7.378±0.05	7.352±0.04
pHcv(n=126)	7.378±0.09	7.364±0.04	7.376±0.05	7.408±0.05	7.370±0.05
PaO2(n=193)	85±19	403±86	436±90	361±89	345±99
PjvO2(n=193)	28±4	35±9	48±25	31±11	38±9
PcvO2(n=126)	34±6	43±10	62±18	42±9	48±10
SaO2(n=193)	97±2	99±0	100±0	100±0	100±0
SjvO2(n=193)	50±9	61±14	75±13	52±16	65±13
ScvO2(n=126)	63±12	73±11	88±7	76±10	80±8
PaCO2(n=193)	35±4	34±5	35±5	30±5	37±5
PjvCO2(n=193)	51±5	51±5	47±5	44±5	49±5
PcvCO2(n=126)	47±7	47±6	42±5	38±6	45±7
ΔPjvCO2(n=193)	-16±4	-17±4	-12±4	-14±5	-12±5
ΔPcvCO2(n=126)	-11±6	-12±5	-8±3	-9±4	-8±5
Lactate-a(n=193)	1.3±0.5	1.4±0.6	1.9±0.6	2.6±0.9	2.7±1.1
Lactate-jv(n=193)	1.3±0.5	1.3±0.5	1.8±0.6	2.6±0.9	2.7±1.2
Lactate-cv(n=126)	1.5±0.7	1.6±0.7	2.1±0.8	3.0±1.0	2.9±1.1

a = artery; jv = jugular vein; cv = central vein; Δ = arterial blood value minus venous blood valu

Table 3. Multivariate regression analyses based on age, surgical time, total input volume, and a blood gas parameter. Log-transformed outcome variables were used in analysis.

Variables	Length of mechanical ventilation			Length of ICU stay			Length of hospital stay		
	Beta	S.E.	P value	Beta	S.E.	P value	Beta	S.E.	P value
Model 1									
Age	0.003	0.002	0.047	0.001	0.001	0.528	0.001	0.001	0.120
Surgical time	0.001	0.000	0.012	0.001	0.000	0.036	0.001	0.000	<0.001
Total input volume	0.000	0.000	0.004	0.000	0.000	<0.001	0.000	0.000	0.015
pHjv-end	-0.672	0.378	0.077	-0.460	0.252	0.069	0.005	0.219	0.982
Model 2									
Age	0.004	0.002	0.080	-0.000	0.002	0.958	0.000	0.001	0.788
Surgical time	0.001	0.000	0.051	0.000	0.000	0.190	0.001	0.000	0.001
Total input volume	0.000	0.000	0.299	0.000	0.000	0.050	0.000	0.000	0.436
pHcv-end	-0.856	0.408	0.038	-0.787	0.267	0.004	-0.234	0.234	0.320
Model 3									
Age	0.003	0.002	0.040	0.001	0.001	0.488	0.001	0.001	0.123
Surgical time	0.001	0.000	0.004	0.001	0.000	0.012	0.001	0.000	<0.001
Total input volume	0.000	0.000	0.004	0.000	0.000	<0.001	0.000	0.000	0.015
PjvCO2-end	0.006	0.122	0.080	0.004	0.002	0.082	0.003	0.002	0.119

ICU = intensive care unit; S.E. = standard error; jv = jugular vein; cv = central vein; end = at the end of surgery

Figures

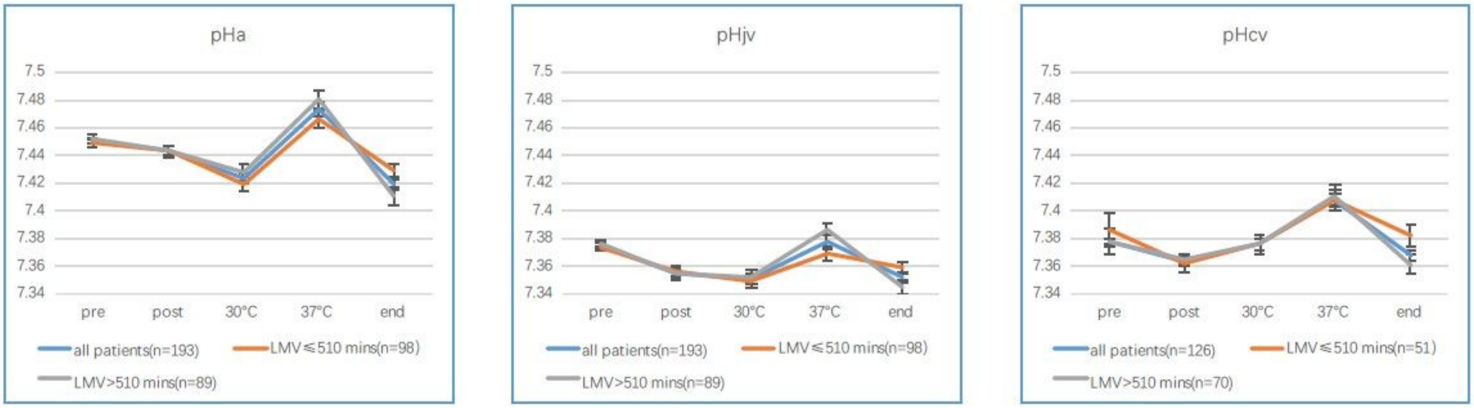

Figure 1

The trends of pH values at different time points in different groups based on the length of mechanical ventilation (LMV). pre = before anesthesia induction; post = after anesthesia induction; 30°C = cardiopulmonary bypass at 30°C; 37°C = cardiopulmonary bypass at 37°C (rewarming); end = at the end of surgery;

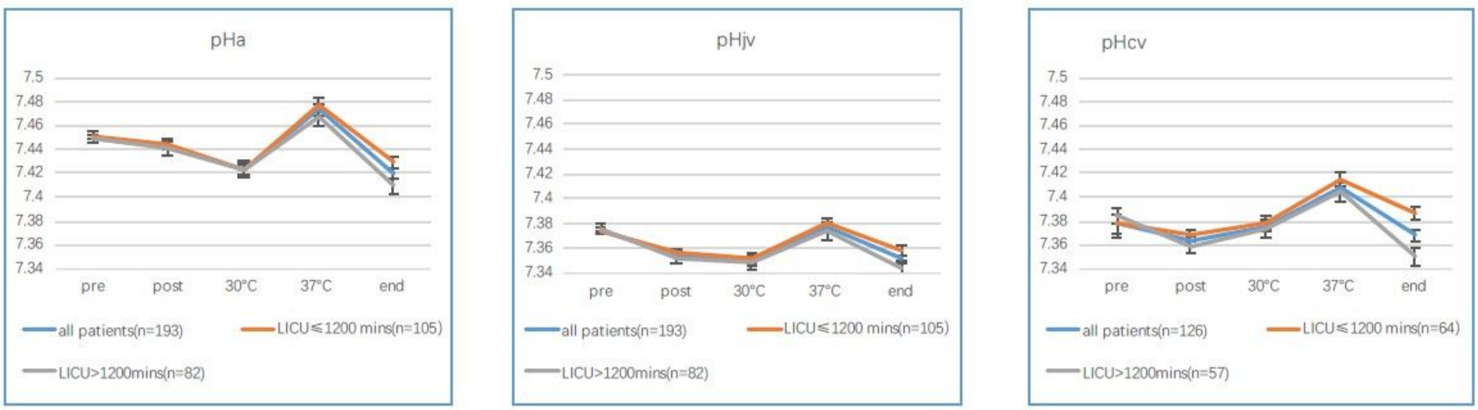

Figure 2

The trends of pH values at different time points in different groups based on the length of intensive care unit stay(LICU). pre = before anesthesia induction; post = after anesthesia induction; 30°C = cardiopulmonary bypass at 30°C; 37°C = cardiopulmonary bypass at 37°C (rewarming); end = at the end of surgery;

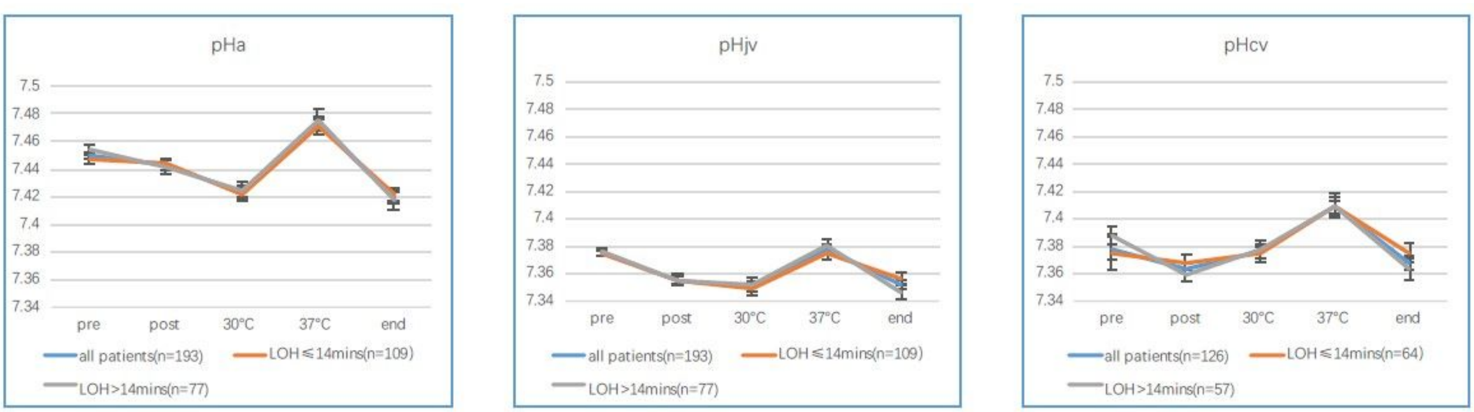

Figure 3

The trends of pH values at different time points in different groups based on the length of hospital stay (LOH) . pre = before anesthesia induction; post = after anesthesia induction; 30°C = cardiopulmonary bypass at 30°C; 37°C = cardiopulmonary bypass at 37°C (rewarming); end = at the end of surgery;

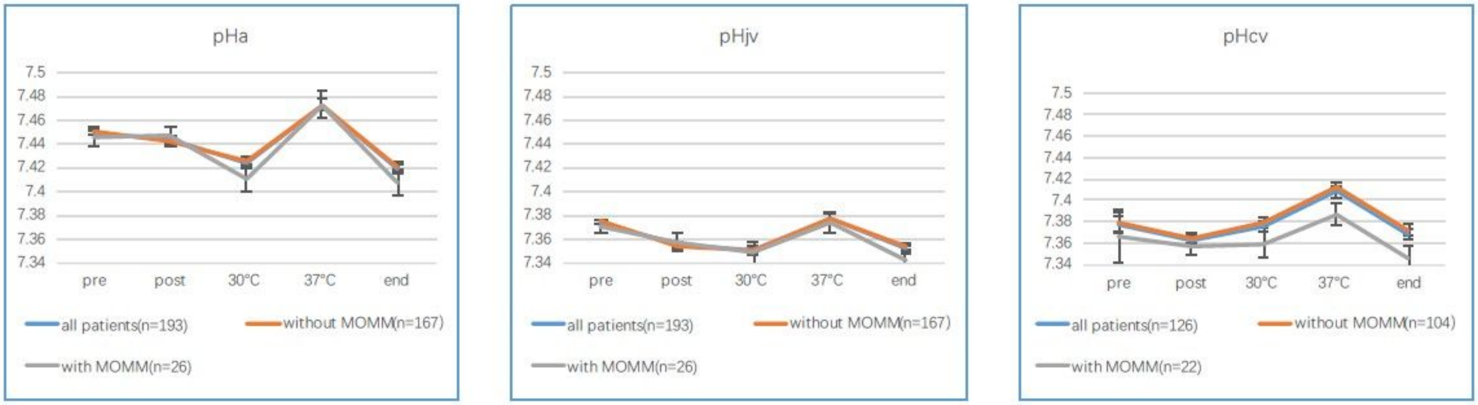

Figure 4

The trends of pH values at different time points in different groups based on without or with major organ morbidity and mortality (MOMM). pre = before anesthesia induction; post = after anesthesia induction; 30°C = cardiopulmonary bypass at 30°C; 37°C = cardiopulmonary bypass at 37°C (rewarming); end = at the end of surgery;

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