ORIGINAL ARTICLE

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Evaluation of Transcutaneous Non-Invasive Blood Gas Analysis for Monitoring Gas Exchange in Pediatric Cardiac Surgical Patients Post Extubation

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This study was carried out at Sri Jayadeva Institute of Cardiovascular Sciences and Research, Bengaluru, India.

ABSTRACT

Introduction: Pediatric cardiac surgery patients need close post-extubation monitoring for ventilation. Non-invasive transcutaneous partial pressure of oxygen ($TcPO_2$) and transcutaneous partial pressure of carbon dioxide ($TcPCO_2$) offer continuous insights and in improving care.
Objective: To investigate the correlation of transcutaneous blood gases ($TcPO_2$, $TcPCO_2$) with arterial blood gases *i.e.* arterial partial pressure of oxygen (PaO_2) and arterial partial pressure of carbon dioxide ($PaCO_2$).
Methods: We conducted a study on 30 pediatric post-cardiac surgery patients (four months to three years old) who were extubated and exhibited stable hemodynamics (inotropic score ≤ 5), normal sinus rhythm, and no respiratory or heart failure signs. Continuous transcutaneous and intermittent arterial blood gas monitoring started one hour after extubation, with recordings every 30 minutes for four hours. A single observer conducted probe calibration and data recording to minimize variability, while analysis of 240 paired samples included correlation coefficient, linear regression, Bland-Altman analysis, and Mountain plot.
Results: The *r*-value between $PaCO_2$ and $TcPCO_2$ was 0.95, r^2-value of 0.9060 (P<0.001). Bland-Altman showed a bias of 2.579, and 95% limits of agreement were -6.4 to 1.3. The *r*-value between PaO_2 and $TcPO_2$ was 0.8942, r^2-value of 0.7996 (P<0.001); bias of 20.171 and 95% limit of agreement of -0.5 to 40.9. The Mountain plot revealed a median of 2.57 for $PaCO_2$ *vs.* TcPCO2 and 20.17 for PaO_2 *vs.* $TcPO_2$.
Conclusion: Transcutaneous carbon dioxide values are interchangeable with arterial $PaCO_2$ in our population study, acting as a surrogate in postoperative pediatric cardiac surgery. Confirmation with arterial blood gases is needed if discrepancies occur.
Keywords: Child, Transcutaneous Blood Gas Monitoring. Carbon Dioxide. Oxygen. Calibration. Heart Failure. Cardiac Surgical Procedures. Hemodynamics.

Abbreviations, Acronyms & Symbols

AARC	= American Association of Respiratory Care	PO_2	= Partial pressure of oxygen
ASD	= Atrial septal defect	SD	= Standard deviation
CO_2	= Carbon dioxide	TCM	= Transcutaneous monitoring
$PaCO_2$	= Arterial partial pressure of carbon dioxide	$TcPCO_2$	= Transcutaneous partial pressure of carbon dioxide
PaO_2	= Arterial partial pressure of oxygen	$TcPO_2$	= Transcutaneous partial pressure of oxygen
PAPVC	= Partial anomalous pulmonary venous connection	TOF	= Tetralogy of Fallot
PCO_2	= Partial pressure of carbon dioxide	VSD	= Ventricular septal defect
PDA	= Patent ductus arteriosus		

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INTRODUCTION

Measurement of arterial blood gases is an integral part of monitoring of respiratory status of the patient. Extubated, postoperative pediatric cardiac surgical patients may become unstable rapidly if they are not monitored closely for hypercapnia and hypoxia. Arterial blood gas analysis remains the "gold standard" monitoring. Transcutaneous partial pressure of carbon dioxide ($TcPCO_2$) monitoring has been done during neonatal transport[1] and in pediatric patients (four years or older) receiving mechanical ventilation for respiratory failure[2]. The American Academy of Sleep Medicine recommends monitoring and reporting of hypoventilation in adults and pediatric population, and arterial partial pressure of carbon dioxide ($PaCO_2$), $TcPCO_2$, or end-tidal partial pressure of carbon dioxide (PCO_2) can be used for detecting hypoventilation during a diagnostic study in both adults and children[3]. However, limited literature is available in extubated postoperative pediatric cardiac surgical patients. The purpose of this study was to observe the correlation of transcutaneous blood gases (transcutaneous partial pressure of oxygen [$TcPO_2$], $TcPCO_2$) with arterial blood gases in such patients.

METHODS

This study was conducted at a tertiary care hospital, in the postoperative pediatric cardiac surgical intensive care unit, after obtaining informed consent from parents and was approved by the Institutional Ethical Committee of the Sri Jayadeva Institute of Cardiovascular Sciences and Research, Bangalore, India.

Inclusion Criteria

Four-month-old to three-year-old pediatric patients who got extubated after cardiac surgery in postoperative pediatric cardiac surgical unit, had an arterial catheter in place with stable hemodynamic parameters, normal sinus rhythm, no residual shunts after cardiac surgery, no signs of cardiac and or respiratory failure, were normothermic, and had a low inotropic score of ≤ 5 were included in the study.

Exclusion Criteria

Patients with unstable hemodynamic parameters, post-repair residual shunts, palliative procedures related to either single ventricle pathology or cyanosis, arrhythmias, signs of respiratory failure, low cardiac output, skin edema, and on high vasopressor support were excluded.

Transcutaneous monitoring (TCM) and arterial blood gas monitoring were started one hour after extubation and continued for four hours by using Draeger $TcPO_2$ and $TcPCO_2$ monitor. Transcutaneous probe calibration was done according to the manufacturer instructions (TINA TCM4, Radiometer, Copenhagen, Denmark). Before placement of transcutaneous probe, calibration was done with gas cylinder which was provided with the instrument. The probe was attached to the dry skin of the right or left upper chest. The working temperature of the probe was kept at 43°C, and the monitor site was changed every two hours to prevent any thermal injury to the patients. The probe was recalibrated before placing it to a new site. To minimize the inter-rater variability, probe calibration, placement, site change monitoring, and recording of data were done by a single observer, and the observer was unaware of arterial blood gas values which were taken every 30 minutes. Arterial blood gases (PCO_2 and partial pressure of oxygen [PO_2]) were recorded at an interval of 30 minutes, and transcutaneous gases ($TcPCO_2$ and $TcPO_2$) were recorded simultaneously, for a period of four hours. The transcutaneous gases' values were displayed on Draeger Infinity delta XL monitor. A set of eight samples for arterial and transcutaneous gases were recorded for each patient.

Statistical Analysis

Sample size was calculated based on a previous study[4], considering correlation coefficient r = 0.9, alpha error = 0.05 with power = 80%. A total of 30 patients were included in the study. Pearson's correlation was done to analyze the correlation coefficient r between transcutaneous gases and arterial gases. A linear regression r^2 and a Bland-Altman analysis[5] were performed to compare the transcutaneous and arterial blood gas values. The bias, measured by Bland-Altman, represents the systemic error or variability between two techniques and is defined as the mean difference between values. Bland-Altman graphs were plotted for visual observation, and 95% confidence limit (limit of agreement) was estimated. In addition, folded cumulative distribution plot (Mountain plot) described by Krouwer and Mont A[6] were also plotted.

A Mountain plot measures the difference of the value obtained by the standard method (arterial blood gases, *i.e.*, arterial partial pressure of oxygen [PaO_2], $PaCO_2$) and the method under investigation (transcutaneous gases, $TcPCO_2$, $TcPO_2$) on the x-axis and the percentile of differences on the y-axis. The resultant plot is inevitably a "mountain." The benefits of the Mountain plot are that it is easier to find the central 95% of the data and easy to estimate percentile for large difference between methods. All the statistical analyses were done with MedCalc software version12.2.1 (Ostend, Belgium).

RESULTS

A total of 30 patients were included, from whom 240 paired samples between transcutaneous and arterial blood gases for both carbon dioxide (CO_2) and oxygen were analyzed. There were 17 male and 13 female patients, their age varied from four months to three years, and their weight varied from 4.4 kg to 17 kg (mean ± standard deviation -10.08 ± 3.15). They underwent various types of intra-cardiac repair (Table 1).

The $TcPCO_2$ was higher than $PaCO_2$ with mean difference of 2.6 ± 1.96 mmHg ($PaCO_2$-$TcPCO_2$). Pearson's correlation coefficient r-value between $TcPCO_2$ and $PaCO_2$ was 0.9519, and linear regression analysis showed r^2-value of 0.9060 (P<0.001) (Figure 1A). Bland-Altman showed a bias of 2.579, and 95% limit of agreement between $PaCO_2$ and $TcPCO_2$ was -6.4 to 1.3 (Figure 1B).

The mean difference between PaO_2 and $TCPO_2$ was 20.2 ± 1.96 mmHg (PaO_2-$TcPO_2$), and PaO_2 was higher (Table 2). The r-value between PaO_2 and $TcPO_2$ was 0.8942, and linear regression analysis showed r^2-value of 0.7996 (P<0.001) which indicates a strong correlation between PaO_2 and $TcPO_2$ (Figure 2A). Bland-Altman analysis of PaO_2 and $TcPO_2$ showed a bias of 20.171 and 95% limit of agreement of -0.5 to 40.9 (Figure 2B). The Mountain plot, which is generally used as complimentary to Bland-Altman plot, also showed similar results where the median $PaCO_2$ and $TcPCO_2$ was small (2.57) and showed small tail (Figure 1C). The median $PaO_2$and $TcPO_2$ was large (20.17), with long tail (Figure 2C).

Table 1. Number of postoperative patients who underwent various types of intracardiac repair.

PDA	ASD	VSD	ASD+VSD	TOF	TAPVC	PAPVC
1	4	11	3	7	2	2

ASD=atrial septal defect; PAPVC=partial anomalous pulmonary venous connection; PDA=patent ductus arteriosus; TOF=tetralogy of Fallot; VSD=ventricular septal defect

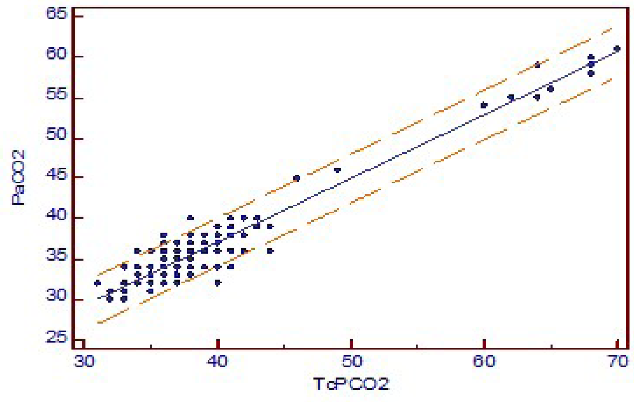

Fig. 1A - *Linear regression analysis of arterial partial pressure of carbon dioxide ($PaCO_2$) versus transcutaneous partial pressure of carbon dioxide ($TcPCO_2$) value. The coefficient of determination r^2 is 0.9060. y = 5.5259 + 0.7893 x.*

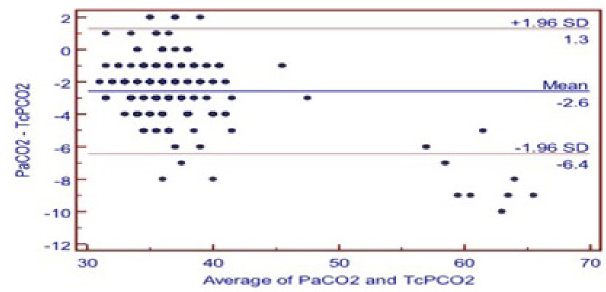

Fig. 1B - *Bland-Altman analysis of agreement between arterial partial pressure of carbon dioxide ($PaCO_2$) and transcutaneous partial pressure of carbon dioxide ($TcPCO_2$). The difference ($PaCO_2$ – $TcPCO_2$) is plotted against the mean ($PaCO_2/2 + TcPCO_2/2$) for each value. The mean difference is -2.6 mmHg and limit of agreement is from -6.4 to 1.3. SD=standard deviation.*

Table 2. Correlation coefficient, linear regression, and Bland-Altman analysis results between transcutaneous and arterial blood gases.

	$PaCO_2$ – $TcPCO_2$	PaO_2 – $TcPO_2$
r-value	0.951	0.894
r^2-value	0.906	0.799
Bias	-2.6	20.2
Limit of agreement	-6.4 to 1.3	-0.5 to 40.9

$PaCO_2$=arterial partial pressure of carbon dioxide; PaO_2=arterial partial pressure of oxygen; $TcPCO_2$=transcutaneous partial pressure of carbon dioxide; $TcPO_2$=transcutaneous partial pressure of oxygen

DISCUSSION

After the analysis, we found that $TcPCO_2$ was accurate and in close agreement with arterial $PaCO_2$ in our postoperative pediatric cardiac surgical population study. Pearson's correlation coefficient *r*-value is 0.9519 ($P<0.001$), which shows a strong positive correlation between $PaCO_2$ and $TcPCO_2$, and Bland-Altman analysis shows a bias of 2.6 and 95% confidence limit of agreement of -6.4 to 1.3 mmHg. The American Association of Respiratory Care (AARC) clinical practice guidelines has cited as clinically acceptable agreement between $TcPCO_2$ and $PaCO_2$ of ± 7.5 mmHg or 1 kPa for TCM of CO_2 and oxygen[7], in 2012. Mountain plot shows median of -2.0, which is very close to "0" and small tail, *i.e.*, less bias and more precise.

In recent studies, Karolina Weinmann et al.[8] did continuous transcutaneous CO_2 monitoring to avoid hypercapnia in complex catheter ablations under conscious sedation and found that it is feasible and precise with good correlation (r=0.60–0.87, $P<0.005$) to arterial blood gas CO_2 analysis under conscious sedation and may contribute to additional safety.

Wang W et al.[9] found, in pediatric laparoscopic surgery, that a close correlation (r^2=0.70, $P<0.01$) was established between $TcPCO_2$and $PaCO_2$. Compared to end-tidal CO_2, transcutaneous CO_2 can estimate $PaCO_2$ accurately and could be used as an auxiliary monitoring indicator to optimize anesthesia management for laparoscopic surgery in children, however, it is not a substitute for end-tidal CO_2.

Michel Toussaint et al.[10] assessed the quality of peripheral oxygen saturation (or SpO_2) and PCO_2 recordings overnight via TCM in children with neurological conditions (out of 64 children, 42 used positive pressure respiratory support). They were able to make satisfactory clinical decisions in 91% of cases and concluded by

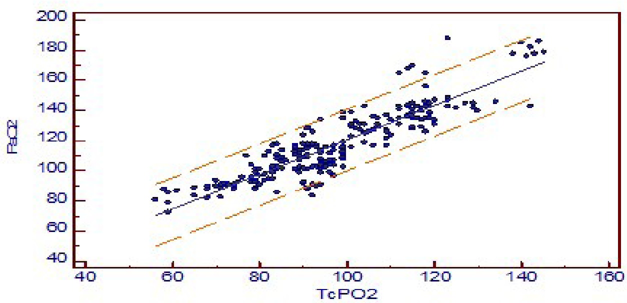

Fig. 2A - *Linear regression analysis of arterial partial pressure of oxygen (PaO_2) versus transcutaneous partial pressure of oxygen ($TcPO_2$) value. The coefficient of determination r^2 is 0.7996. y = 6.6815 + 1.1394 x.*

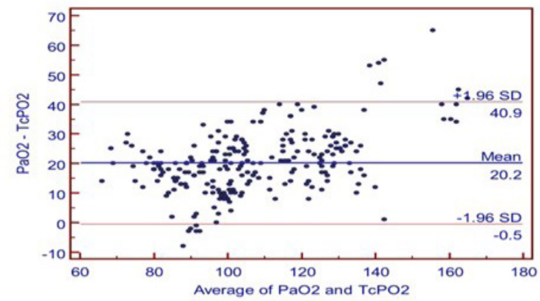

Fig. 2B - *Bland-Altman analysis of agreement between arterial partial pressure of oxygen (PaO_2) and transcutaneous partial pressure of oxygen ($TcPO_2$). The difference (PaO_2 – $TcPO_2$) is plotted against the mean ($PaO_2/2$ + $TcPO_2/2$) for each value. The mean difference is 20.2 mmHg and limit of agreement is from -0.5 to 40.9. SD=standard deviation.*

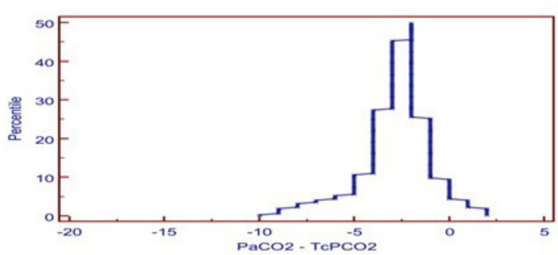

Fig. 1C - *Mountain plot analysis between arterial and transcutaneous carbon dioxide. Values vary from 2.00 to -10.00. Median is -2.00. $PaCO_2$=arterial partial pressure of carbon dioxide; $TcPCO_2$=transcutaneous partial pressure of carbon dioxide.*

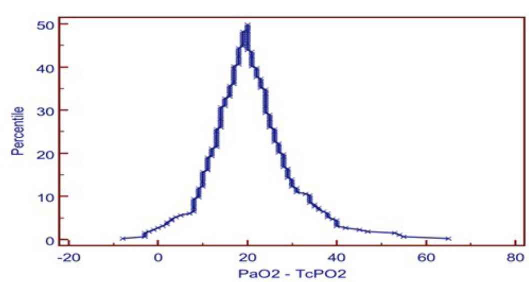

Fig. 2C - *Mountain plot analysis between arterial and transcutaneous oxygen. Values vary from -8.00 to 65.00. Median is 20.00. PaO_2=arterial partial pressure of oxygen; $TcPO_2$=transcutaneous partial pressure of oxygen.*

saying that the quality of transcutaneous sensor recordings was acceptable, and clinical findings were deemed as satisfactory in the large majority of cases. Many studies have not only shown a strong correlation between the $TcPCO_2$ and $PaCO_2$, but also positively validated accuracy, high degree of interchangeability, and that sometimes and it may provide a better estimate of $PaCO_2$ than end-tidal CO_2 in pediatric population[11-15].

In 2019, a systemic review and meta-analysis for precision and accuracy of transcutaneous CO_2 monitoring by Aron Conway et al.[16] has identified that there may be substantial differences between $TcPCO_2$ and $PaCO_2$ depending on the context in which this technology is used in clinical practice, but in their meta-analysis, the population limits of agreement between transcutaneous and arterial CO_2 in pediatric intensive care unit and surgery was -5.1 to 4.4 mmHg, which was an acceptable agreement between $TcCO_2$and $PaCO_2$ (± 7.5 mm Hg or 1 kPa)[16].

Regarding transcutaneous oximetry ($TcPO_2$), we found Pearson's correlation coefficient *r*=0.894, and linear regression analysis showed r^2-value of 0.7996 (P<0.001) which has a strong positive correlation between $TcPO_2$ and PaO_2, and when comparing with Bland-Altman analysis, it revealed a bias of 20.17 and wide limit of agreement. On Mountain plot analysis for PaO_2 and $TCPO_2$, the median between PaO_2 and $TcPO_2$ was 20.17, with long tail, indicating less precise and poor interchangeability.

Several studies have demonstrated that $TCPO_2$ is not generally reliable[15,17] and have also found to have a poor correlation, wide limit of agreement between $TcPO_2$ and PaO_2, and suggested that $TCPO_2$ cannot be surrogate to PaO_2.

TCM of gases really measures $TcPO_2$ and $TcPCO_2$, not PaO_2 and $PaCO_2$[11], that could be the possible reason for the clinically acceptable difference between $PaCO_2$ and $TcPCO_2$ be ± 7.5 mmHg, as per AARC clinical guidelines[7].

$TcPO_2$ is an indirect measurement of PaO_2 and does not reflect oxygen delivery or oxygen content. Complete assessment of oxygen delivery requires knowledge of hemoglobin saturation and cardiac output. $TcPCO_2$ is an indirect measurement of $PaCO_2$, but knowledge of delivery and content is not necessary to use TCM ($TcPCO_2$) for assessment of ventilation.

TCM has traditionally been done by placing a heated sensor on the skin that increases the capillary blood flow and amount of oxygen diffusing to the sensor. Due to different diffusion rates, monitoring $TcPCO_2$ can typically be achieved using lower temperatures of

38-42°C, which is not feasible for $TcPO_2$, where temperature has to be kept at 43-44°C to achieve precise results[18].

Epidermal and dermal cells consume oxygen and produce CO_2, therefore $TcPO_2$ is lower than PaO_2 and $TcPCO_2$ is higher than $PaCO_2$ irrespective of the sensor measuring temperature. This influence is minimized by applying a temperature-specific constant and a metabolic factor by the manufacturers[19,20].

Arterial blood gas analysis is a gold standard technique but provides only momentary status. It is time consuming, and repeated sampling might lead to blood loss and anemia especially in neonates and pediatric postoperative cardiac surgical patients. Liebowitz RS et al.[21] concluded that there is low but measurable morbidity associated with arterial catheterization as well. TCM is a continuous, noninvasive method, but transcutaneous probe placement requires expertise — improper placement, damaged membranes, trapped air bubbles, and inappropriate calibration techniques may affect its accuracy. Patient problems such as tissue hypoperfusion, the presence of edema, low cardiac output, and hypothermia may affect the measurements. Several studies have documented that vasoactive substances like dopamine, epinephrine, dobutamine, and norepinephrine did not affect $TcPCO_2$/$TcPO_2$ measurements[7,22,23].

Limitations

Limitations of the study were: this is a single-center, observational study, only patients with stable hemodynamic parameters without residual shunt and arrhythmias were studied, monitoring of the patients for a very limited time, and the fact that pH, base excess or deficit, serum electrolyte, hematocrit, and lactate cannot be obtained by this instrument. We need further larger randomized control studies to assess whether trends of changes in transcutaneous gases values can be reliable in post cardiac surgery pediatric patients.

CONCLUSION

CO_2 values obtained from TCM are interchangeable with those obtained from arterial blood gas analysis in our population study, unlike oxygen measurements which are not interchangeable. Hence $TcPCO_2$ values can be used as a surrogate for arterial $PaCO_2$ measurements in postoperative pediatric cardiac surgical patients. However, arterial blood gas analysis should be performed when transcutaneous gases do not appear consistent with clinical findings.

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Authors' Roles & Responsibilities

GP	Substantial contributions to the conception or design of the work; or the acquisition, analysis, or interpretation of data for the work; final approval of the version to be published
SPB	Substantial contributions to the conception or design of the work; and the analysis or interpretation of data for the work; final approval of the version to be published
AG	Substantial contributions to the conception or design of the work; and the analysis or interpretation of data for the work; final approval of the version to be published
NGS	Substantial contributions to the conception or design of the work; and the analysis or interpretation of data for the work; final approval of the version to be published

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