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ORIGINAL ARTICLE

A Prospective Observational Study on Role of Intraoperative Renal & Muscle Oxygen Saturation on Post-operative Serum Creatinine Level in Patients Undergoing Cardiac Surgery on Cardiopulmonary Bypass

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Abstract

Objective: **Near-infrared spectroscopy (NIRS), can be used to monitor renal tissue oxygenation (SrO_2), as well as thenar muscle oxygenation (SmO_2). In this study, we have examined the ability of SrO_2 and SmO_2 in predicting cardiac surgery related change in serum creatinine level (ΔsCr) and explored any correlation between these two parameters.**

Methods: **This study included 55 adult patients (18−60 years), who were scheduled for elective cardiac surgery with cardiopulmonary bypass (CPB), having no pre-existing renal impairment, with skin-to-kidney depth of <4 cm at superior lumbar region which was detected by preoperative ultrasonography examination. NIRS sensors were applied on the superior lumber region to measure SrO_2 and on thenar eminence for SmO_2, preoperatively. ΔsCr was investigated at 24, 48 and 72 hours post-operatively. Relative thresholds of SrO_2 and SmO_2 were quantified using the area-under curve; expressed in % min.**

Results: **Area under the receiver-operating characteristic curve (AUROC) analyses showed SrO_2 decrease >20 % from baseline can significantly predict (AUROC 0.921; $p = 0.001$) post-operative ΔsCr. SmO_2 decreased 15 % from baseline (AUROC 0.843; $p = 0.001$) is a better predictor of ΔsCr than its fall >20 % from baseline (AUROC 0.749; $p = 0.002$). Correlation analysis revealed that the 15 % and >20 % decrease of SmO2 below baseline (Spearman's rho 0.593 and 0.606 respectively) had significant ($p = 0.01$) positive correlation with decrease of SrO_2 >20 % from baseline.**

Conclusion: **SrO_2 and SmO_2 have significant predictive values for post-cardiac surgery rise in serum creatinine, and there is strong positive correlation between them.**

Keywords: Renal oxygen saturation, Muscle oxygen saturation, Serum creatinine, Cardiac surgery, Cardiopulmonary bypass

1. Introduction

Acute kidney injury (AKI) following open cardiac surgery involving cardiopulmonary Bypass (CPB) is a common and serious complication. Ample description on etiology of post-cardiac surgery AKI is found in literature, which not only consists of metabolic abnormalities, ischemia-reperfusion injuries, inflammatory mediators, but also, non-physiological (non-pulsatile flow) circulation by CPB, hypothermia, hemodilution by CPB priming volume, hemolysis, blood product

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transfusions are notably responsible for developing AKI [1].

Renal injury biomarkers like Cystatin C, NGAL etc., lack the ability to measure real-time renal function. Near-infrared spectroscopy (NIRS) is a non-invasive, real-time monitoring system, that measures oxygenation at the tissue level. NIRS has been used at renal [2], and thenar muscle regions [3,4] to measure tissue oxygenation. Studies have demonstrated significantly higher amounts of tissue deoxygenation at renal regions in cardiac cases undergoing cardiopulmonary bypass (CPB) [5].

Intraoperative renal tissue deoxygenation has been found to be associated with post-operative renal dysfunction in Ref. [2] cardiac surgeries. Studies have reported that even mild rise in sCr (0−0.3 mg/dl) after cardiac surgery can be significantly associated with morbidity and mortality [6−9].

NIRS sensors measure regional tissue oxygenation only up to a tissue depth <4 cm from skin surface [10,11]. Practical limitations of renal tissue NIRS include inaccurate reading in obesity, i.e., with skin to tissue depth >4 cm, difficult access to supra-renal region intra-operatively, and chances of sensor soiling with blood, skin preparation liquid etc. To overcome these limitations, thenar muscle NIRS could be used as an alternative.

Like renal regional desaturation (SrO_2), evidence of muscle regional desaturation (SmO_2) predicting post-surgical renal dysfunction [5]; is available in literature. Unlike SrO_2, there is a lack of consensus regarding cut-off values for SmO_2. Also, it is not clear if there is a correlation between SrO_2 and SmO_2.

Hence, we designed this study to evaluate how well SrO_2 and SmO_2 can predict post-operative rise in serum creatinine, and secondarily to see if there is any correlation between these two parameters.

Abbreviations

AKI	Acute kidney injury
ACT	Activated clotting time
AUC	Area under curve
AUROC	Area Under the Receiver Operating Characteristic Curve
ASA	American Society of Anesthesiologists
BIS	Bi-Spectral index
CDC	Center for Disease Control and Prevention
CI	Cardiac index
CPB	Cardiopulmonary bypass
CVP	Central venous pressure
ΔsCr	Increase in serum creatinine
FiO_2	Fraction of inspired oxygen
IBP	Invasive blood pressure
NIRS	Near-infrared spectroscopy
RIFLE	Risk, Injury, Failure, Loss of kidney function, and End-stage kidney disease
SpO_2	Peripheral oxygen saturation
SmO_2	Muscle regional saturation
SrO_2	Renal regional saturation

2. Materials and methods

2.1. Recruitment of study participants

This prospective observational study was conducted in a tertiary care medical hospital in a period of 18 months, as per the institutional guidelines, after obtaining approval from the Institutional Ethics Committee (Memo No. RKC/755, dated 14.01.2023). The study was conducted in accordance with the World Medical Association Declaration of Helsinki. The study population included was, all the adult patients undergoing elective open heart surgery with cardiopulmonary bypass at the cardiothoracic surgery operation theatre of RG Kar Medical College and Hospital. Randomization was done using Kevin Conroy: 5120 Random Numbers (<5 k, 2002) [Call the JavaScript pseudo-random number generator.]. Sample size calculation was done using Epi Info (TM) 7.2.2.2, which is a trademark of the Center for Disease Control and Prevention (CDC). Ortega-Loubon et al. [10] in their study recorded kidney oxygen saturation during intra-operative period in patients undergoing cardiac surgery. The study showed that decrease in kidney oxygen saturation less than 65 % from baseline showed positive correlation for acute kidney injury prediction. Thus, for this study $p = 0.65$., where the formula used for sample size calculation was $n = 4pq/L^2$, referring 'n' as the required sample size, 'q' as '$(1-p)$', 'L' as Loss% (Loss of information = 20 %). The minimum number of patients required for this study was 53.84−54 with power 80 %. Patients aged between 18 and 60 years of both sexes, posted for elective open cardiac surgery, were subjected to an ultrasound examination, to include those with skin-to-kidney depth of <4 cm at superior lumber region. Unwilling patients, patients with pre-existing renal impairment (serum creatinine concentration more than 1.5 mg/dl), patients having some pathologies on their upper limbs; like trauma, burn, complex regional pain syndrome, carpal tunnel syndrome and any skin changes that might not allow proper placement of NIRS sensors were excluded from the study. Written informed consent was obtained from all the participating patients, and their privacy rights had been observed.

2.2. Measurements

NIRS sensors were placed on the left flank, at the level between costal margin and iliac crest for SrO_2 and on thenar eminence for SmO_2. SrO_2 and SmO_2 were measured noninvasively and continuously by NIRS with the INVOS 5100 Regional Oximeter (Medtronic, Minneapolis, USA). Baseline SrO_2 and SmO_2 values were recorded before the induction of anesthesia in room air. Relative thresholds of SrO_2 and SmO_2 were quantified using the area-under curve (AUC), expressed in %min, representing both magnitude and duration of desaturation below set thresholds. Relative changes were calculated from the AUC for >20 % below baseline SrO_2 and the AUC for 10 %, 15 %, >20 % below baseline SmO_2.

2.3. Anesthesia and CPB conduction

Pre-anesthetic evaluation was performed in each patient which included detailed history taking, thorough physical examination and relevant preoperative investigations. The nature and procedure of the study was explained to the patients. On arrival at the operation room, ASA standard monitors were attached. Central venous cannulation and arterial cannulation were done under local anesthesia and mild sedation with 0.05 mg/kg Midazolam, 1 μg/kg Fentanyl. Patient monitors included Pulse oximetry, Electrocardiography, Invasive arterial blood pressure (IBP), central venous pressure (CVP), core temperature monitoring at nasopharynx, depth of anesthesia monitoring with a BIS 4 Electrode Sensor (Medtronic, Ontario, Canada), renal & muscle regional oximetry monitoring by NIRS sensors and urine output monitoring.

Anesthesia induction was done with IV injection of 0.05 mg/kg Midazolam, Fentanyl 5 μg/kg and Propofol 1.5 mg/kg. Tracheal intubation was done following administration of 1 mg/kg Rocuronium IV. After intubation, patients were ventilated with air/O_2 mixture with Drager Atlan A350 Anesthesia workstation in volume-controlled mode. FiO_2 after intubation was set at 50 % and was adjusted according to blood gas analysis and SpO_2, to maintain SpO_2 95 %−100 %. Throughout the procedure, anesthesia was maintained with boluses of 50 μg Fentanyl and 10 mg Rocuronium. IV 10 mg Propofol boluses and inhaled Sevoflurane were used to keep intraoperative BIS in the range of 40−60. Heparin was administered @400 IU/kg intravenously, 3 minutes prior to aortic cannulation to achieve ACT >480 s. Patients were connected to the CPB machine once the cannulations were completed. Target flow rate of 2.4 L/min/m^2 was maintained by non-pulsatile CPB. PaO_2, $PaCO_2$, and serum bicarbonate (HCO_3-) were maintained within normal physiological limits during CPB. Perioperative fluid management was done by adjusting hemodynamic parameters like heart rate, IBP and transesophageal echocardiography parameters like IVC diameter, stroke volume index and cardiac index. After completion of surgery, patients were transferred to ICU under sedation with 0.5 μg/kg/hour infusion of Dexmedetomidine, and such was continued until patient becomes ready for extubation.

2.4. Statistical analysis

Raw data of study parameters were analyzed by standard statistical software (SPSS version 24). Normally distributed data were tested with Shapiro−Wilk test. The area-under the receiver-operating characteristic curve (AUC ROC) analyses were used to compare predictive power of measured parameters. Correlation analysis was done using Spearman's rho-coefficient of correlation for non-normal data distribution. 'p' value of <0.05 was considered as statistically significant.

3. Results

During the period of study, 55 adult patients meeting inclusion criteria were recruited in our study. We could analyze all 55 patients. 24 (43.6 %) patients had developed small increase in serum creatinine (ΔsCr = at least 0−0.3 mg/dl) post-operatively. Data regarding patient characteristics and clinical information of study population has been shown in Table 1.

As shown in Fig. 1, the AUC ROC analysis revealed that SrO_2 decrease >20 % from baseline can significantly predict (AUROC 0.921; 95 % CI 0.990 to 0.851; $p = 0.001$) post-operative ΔsCr. It was also found from AUC ROC analysis of SmO_2 that, 15 % decrease from baseline (AUROC 0.843; 95 % CI 0.951 to 0.734; $p = 0.001$) is a better predictor of ΔsCr than the fall of >20 % from baseline (AUROC 0.749; 95 % CI 0.879 to 0.619; $p = 0.002$).

Correlation analysis in Table 2 showed that the 15 % and >20 % (Spearman's rho coefficients of correlation 0.593 and 0.606 respectively) fall of SmO_2 from baseline have significant (at the 0.01 level (2-tailed)) positive correlation with decrease of SrO_2 >20 % from baseline.

4. Discussion

Increase in serum creatinine after cardiac surgery can increase morbidity, mortality and financial

Table 1. Patient characteristics, clinical information of study population (n = 55).

Variables	Values
Age in years, (mean ± SD)	37.7 ± 9.96
Sex = Male: Female (n)	24 : 31
BMI in kg/m2 (mean ± SD)	22.51 ± 1.62
LVEF in % (mean ± SD)	57.54 ± 6.49
Pre-operative serum Creatinine in mg/dl (mean ± SD)	0.82 ± 0.11
Depth of Kidney in cm (mean ± SD)	2.68 ± 0.61
Type II Diabetes Mellitus, n (%)	17 (30.9)
Hypertension, n (%)	9 (16.4)
Types of surgery, n (%)	
On-Pump CABG	6 (11)
Mitral valve replacement	15 (27.3)
Aortic valve replacement	9 (16.3)
Double valve replacement	7 (12.7)
CABG + valve replacement	4 (7.3)
ASD repair	9 (16.3)
VSD repair	5 (9.1)
CPB time in minutes (mean ± SD)	82.5 ± 14.1
Cross-clamp time minutes (mean ± SD)	46.16 ± 11.34
Baseline SrO_2 (mean ± SD)	77.3 ± 2.76
Baseline SmO_2 (mean ± SD)	77.1 ± 2.77

Table 2. Correlation analysis between decrease of SrO_2 with decrease of SmO_2.

SmO_2	SrO_2		
	Decreased SrO_2 20 % from baseline		
	Spearman's rho coefficient of correlation	Sig. (2-tailed)	N
Decreased SmO_2 20 % from baseline	0.606	0.01	55
Decreased SmO_2 15 % from baseline	0.593	0.01	55

burden of patients [6,9,12]. Near-Infrared Spectroscopy (NIRS) can monitor regional tissue perfusion non-invasively and has been used at renal as well as the thenar muscle region to monitor tissue oxygenation [2,3]. Thenar muscle is superficial and easily accessible, thus overcoming the limitations of renal NIRS, which are variable tissue depth (NIRS can monitor regional tissue oxygenation at < 4 cm depth), poor access as well as chances of soiling of sensors with blood intra-operatively.

In the prospective observational study conducted by Choi et al. [2], on 100 patients undergoing cardiac surgery, SrO_2 was continuously monitored throughout the anesthetic period by NIRS and RIFLE criteria was used to define post-operative AKI. They had found that, significantly longer periods of renal desaturation were present (absolute SrO_2 <55 %) in patients who developed AKI. In a case-control study conducted by Ruf et al. [13], intra-operative renal oximetry measured by NIRS was found to be significantly lower in the infants who developed AKI (defined by pRIFLE classification). According to them, low SrO_2 during cardiac surgery might be a superior marker of AKI than conventional biomarkers as they increased much later. In a prospective cohort study on 121 adult

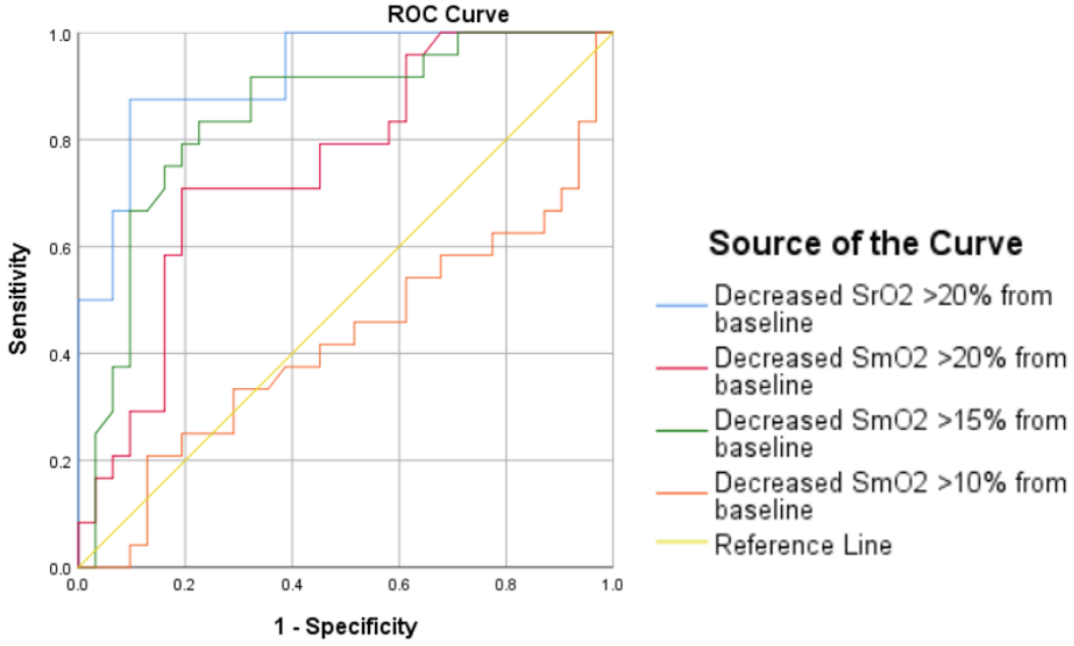

Fig. 1. Area-under the receiver-operating characteristic curve analysis for predictive powers of SmO_2 & SrO_2 at different thresholds to predict post-operative rise in serum creatinine.

patients, Ortega-Loubon et al. [10], attached the NIRS sensors to the flanks, after excluding patients with skin to renal depth of 4 cm or more. Their receiver-operating characteristic curve analysis revealed a 20 % decrease of SrO2 from baseline had good predictive values (p value 0.019) for predicting cardiac surgery associated AKI. They also commented that area declined from baseline appeared to be a better parameter than an absolute NIRS measurement, because it reflects both magnitude and duration of desaturation.

In our study (43.6 %) patients had developed small increase (at least 0−0.3 mg/dl) in serum creatinine post-operatively. Post-operative rise in serum creatinine may not meet the conventional AKI classifications due to dilutional effects of CPB [14]. Studies have reported that small rise in serum creatinine can significantly be associated with morbidity and mortality [7,15]. Corroborating with earlier studies, the AUC ROC analysis revealed that SrO_2 decrease >20 % from baseline can significantly predict (AUROC 0.921; 95 % CI 0.990 to 0.851; $p = 0.001$) post-operative ΔsCr.

On the contrary, Keijer et al. [15] did not find any association between renal regional oxygenation values and post-operative renal impairment in a retrospective ($n = 41$) study. They criticized the reason behind such findings to be lack of systemic recording of kidney depth. On the other hand, their results revealed >10 % decrease fall from baseline peripheral tissue oxygenation at the thenar muscle region appeared to be a good predictor of post-operative renal impairment. Thenar muscle oximetry was monitored on 114 adult patients undergoing cardiac surgery with CPB in the study conducted by Szymanowicz et al. [16] NIRS values recorded 20 minutes after CPB was found to be the most accurate predictor of cardiac surgery related AKI. <54.5 % as absolute cut-off value of SmO_2 was found to have Odd's Ratio (OR) of 6.87 for predicting AKI.

AUC ROC analysis of SmO_2 in our study showed that, both 15 % decrease (AUROC 0.843; 95 % CI 0.951 to 0.734; $p = 0.001$) and >20 % decrease from baseline (AUROC 0.749; 95 % CI 0.879 to 0.619; $p = 0.002$) are good predictors of post-operative ΔsCr. But 15 % decrease is a better predictor than >20 % fall from baseline. Data analyzed from 150 adult patients who had undergone elective cardiac surgery, showed that a <67 % thigh muscle regional oximetry during CPB could predict AKI within 24 hours post-surgery [17]. One study [18] conducted on 394 patients undergoing cardiac surgery revealed planter muscle regional saturation <45 %, independent of mean arterial pressure was related to increased risk of AKI.

We designed this study also to see if there is any correlation between decrease of SmO_2 and decrease of SrO_2. Spearman's rho coefficient of correlation analysis showed positive correlation between 15 % fall of SmO_2 and >20 % fall of SrO_2 from baseline values (Spearman's rho 0.593). Strong positive correlation was found between >20 % fall of SmO_2 and >20 % fall of SrO_2 from baseline values (Spearman's rho 0.606). *Hardly any study was found in the available literature involving human subjects to explore any relation between fall of SmO_2 at the thenar muscle region with fall of SrO_2.* Only a recent study [19] on experimental animal model revealed strong correlation between kidney NIRS signals (correlation coefficient, $r = 0.85$ & $r = 0.88$, for left and right kidney respectively) and thigh NIRS measurements.

Limitation: Long-term follow-up has not been done to see if there can be any long-term implications of peripheral muscle desaturation during cardiac surgery with CPB. Interventions to improve decreased SrO_2 and SmO_2 to prevent post-surgical rise in serum creatinine have not been explored.

5. Conclusions

Renal regional oxygen saturation and thenar muscle regional oxygen saturation measured by NIRS can significantly predict cardiac surgery associated rise in serum creatinine. There was a strong positive correlation between renal regional oxygen saturation and thenar muscle oxygen saturation. Therefore, SmO_2 could be a user-friendly and error-free substitute for SrO_2.

6. Consent to participate

Written informed consent was obtained from all the patients included in the study.

Ethics approval

This study was conducted after obtaining ethical approval (Memo No. RKC/755, date 14.01.2023) from the Institutional Ethics Committee registered with the Drug Controller General India; Reg No. (ECR/322/Inst/WB/2013/RR-20).

Author contributions

Conception and design of Study: BB, HD, LS, DM. Literature review: SP, DM. Acquisition of data: BB, LS, SP, DM. Analysis and interpretation of data: BB, DM. Research investigation and analysis: BB, HD, SP,

DM. Data collection: LS, SP, DM. Drafting of manuscript: LS, SP, DM. Revising and editing the manuscript critically for important intellectual contents: BB, HD, LS, SP, DM. Data preparation and presentation: LS, DM. Supervision of the research: BB, HD. Research coordination and management: BB, HD.

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Conflicts of interest

None to declare.

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References

[1] Mao H, Katz N, Ariyanon W, Martos LB, Adýbelli Z, Giuliani A, et al. Cardiac surgery-associated acute kidney injury. Cardiorenal Med 2013;3:178–99. https://doi.org/10.1159/000353134.

[2] Choi DK, Kim WJ, Chin JH, Lee EH, Hahm KD, Sim JY, et al. Intraoperative renal regional oxygen desaturation can be a predictor for acute kidney injury after cardiac surgery. J Cardiothorac Vasc Anesth 2014;28(3):P564–81. https://doi.org/10.1053/j.jvca.2013.12.005.

[3] Duret J, Pottecher J, Bouzat P, Brun J, Harrois A, Payen JF, et al. Skeletal muscle oxygenation in severe trauma patients during haemorrhagic shock resuscitation. Crit Care 2015;19:1–7. https://doi.org/10.1186/s13054-015-0854-4.

[4] Biedrzycka A, Kowalik M, Pawlaczyk R, Jagielak D, Swietlik D, Szymanowicz W, et al. Aortic cross-clamping phase of cardiopulmonary bypass is related to decreased microvascular reactivity after short-term ischaemia of the thenar muscle both under intravenous and volatile anaesthesia: a randomized trial. Interact Cardiovasc Thorac Surg 2016;23:770–8. https://doi.org/10.1093/icvts/ivw232.

[5] Keijzer IN, Poterman M, Absalom AR, Vos JJ, Mariani MA, Scheeren TWL. Comparison of renal region, cerebral and peripheral oxygenation for predicting postoperative renal impairment after CABG. J Clin Monit Comput 2022;36:735–43. https://doi.org/10.1007/s10877-021-00701-4.

[6] Lassnigg A, Schmidlin D, Mouhieddine M, Bachmann LM, Druml W, Bauer P, et al. Minimal changes of serum creatinine predict prognosis in patients after cardiothoracic surgery: a prospective cohort study. J Am Soc Nephrol 2004;15:1597–605. https://doi.org/10.1097/01.asn.0000130340.93930.dd.

[7] Lassnigg A, Schmid ER, Hiesmayr M, Falk C, Drumi W, Bauer P, et al. Impact of minimal increases in serum creatinine on outcome in patients after cardiothoracic surgery : do we have to revise current definitions of acute renal failure? Crit Care Med 2008;36(4):1129–37. https://doi.org/10.1097/ccm.0b013e318169181a.

[8] Kolli H, Rajagopalam S, Patel N, Ranjan R, Venuto R, Lohr J, et al. Mild acute kidney injury is associated with increased mortality after cardiac surgery in patients with EGFR <60 ml/min/1.73m2. Ren Fail 2010;32:1066–72. https://doi.org/10.3109/0886022x.2010.510616.

[9] Bernardi MH, Risti R, Neugebauer T, Hiesmayr MJ, Drumi W, Lassnigg A. Very early changes in serum creatinine are associated with 30-day mortality after cardiac surgery. Eur J Anaesthesiol 2020;37:898–907. https://doi.org/10.1097/eja.0000000000001214.

[10] Ortega-Loubon C, Fernandez-Molina M, Fierro I, Monjas PJ, Carrascal Y, Herreras JIG, et al. Postoperative kidney oxygen saturation as a novel marker for acute kidney injury after adult cardiac surgery. J Thorac Cardiovasc Surg 2019;157:2340–51. https://doi.org/10.1016/j.jtcvs.2018.09.115.

[11] Tholen M, Ricksten SE, Lannemyr L. Renal near-infrared spectroscopy for assessment of renal oxygenation in adults undergoing cardiac surgery : a method validation study. J Cardiothorac Vasc Anesthesia 2020;34(12):P3300–5. https://doi.org/10.1053/j.jvca.2020.04.044.

[12] Elghoneimy YA, Al Qahtani A, Almontasheri SA, Tawhari Y, Alshehri M, Alshahrani AH, et al. Renal impairment after cardiac surgery: risk factors, outcome and cost effectiveness. Cureus 2020;12(11):e11694. https://doi.org/10.7759/cureus.11694.

[13] Ruf B, Bonelli V, Balling G, Hörer J, Nagdyman N, Braun SL, et al. Intraoperative renal near-infrared spectroscopy indicates developing acute kidney injury in infants undergoing cardiac surgery with cardiopulmonary bypass: a case-control study. Crit Care 2015;19(1):27. https://doi.org/10.1186/s13054-015-0760-9.

[14] Ortega-Loubon C, Fernandez-Molina M, Carrascal-Hinojal Y, Fulquet-Carreras E. Cardiac surgery-associated acute kidney injury. Ann Card Anaesth 2016;19:687–98. https://doi.org/10.4103/0971-9784.191578.

[15] Kopp R, Dommann K, Rossaint R, Schalte G, Grottke O, Spillner J, et al. Tissue oxygen saturation as an early indicator of delayed lactate clearance after cardiac surgery: a prospective observational study. BMC Anesthesiol 2015;15:158. https://doi.org/10.1186/s12871-015-0140-7.

[16] Szymanowicz W, Daniłowicz-Szymanowicz L, Karolak W, Kowalik MM, Lango R. Brain and muscle oxygen saturation combined with kidney injury biomarkers predict cardiac surgery related acute kidney injury. Diagnostics 2021;11:1591. https://doi.org/10.3390/diagnostics11091591.

[17] Sakaki K, Kitamura T, Kohira S, Torii S, Mishima T, Hanayama N, et al. Regional thigh tissue oxygen saturation during cardiopulmonary bypass predicts acute kidney injury after cardiac surgery. J Artif Organs 2020;23:315–20. https://doi.org/10.1007/s10047-020-01175-y.

[18] Ju JW, Yoo SJ, Park D, Bae J, Lee S, Nam K, et al. Association between intraoperative planter regional oxygen saturation and acute kidney injury after cardiac surgery. J Clin Monit Comput 2023;37:525–40. https://doi.org/10.1007/s10877-022-00917-y.

[19] Silverton NA, Lofgren LR, Kuck K, Stoddard GJ, Johnson R, Ramezani A, et al. Near-infrared spectroscopy for kidney oxygen monitoring in a porcine model of hemorrhagic shock, hemodilution, and REBOA. Sci Rep 2024;14:2646. https://doi.org/10.1038/s41598-024-51886-y.