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Monitoring of Perfusionists' Cognitive Load and Stress and Patients' Oxygen Delivery during Cardiopulmonary Bypass in Cardiac Surgery

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INTRODUCTION

Cardiopulmonary bypass (CPB) during cardiac surgery represents a critical phase where perfusionists must continuously monitor and adjust multiple physiological parameters to maintain adequate tissue oxygenation. [1] Among these, oxygen delivery (DO2) is a crucial indicator of patient perfusion adequacy and is associated with postoperative outcomes.[2] Although previous research suggests that cognitive overload may impair performance in the operating room (OR), the relationship between patient DO2 levels and the cognitive demands imposed on perfusionists remains poorly understood. This study aimed to investigate the relationship between patient DO2 levels and perfusionists' cognitive load and stress measured through heart rate variability (HRV) during the CPB phase of cardiac surgery.

MATERIALS AND METHODS

Study Setting and Design:

This was a prospective observational study conducted in the cardiac operating room (OR) of a tertiary hospital in the United States. The Institutional Review Board (IRB) approved the research protocol, and informed consent was obtained from all participants.

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Population:

Perfusionists who worked in the cardiac OR and patients who were undergoing open cardiac surgery procedures: coronary artery bypass grafting (CABG) and/or aortic valve replacement (AVR).

Procedures:

As part of the regular OR operational procedures, all cardiac patients had an in-line monitoring system (*CDI Blood Parameter Monitoring System 550* by Terumo) providing continuous information on key blood parameters, including the DO2 levels at a 3-minute window. During the CPB phase, this system provides the perfusionists with information about the patient's perfusion status with DO2 indexed to body surface area (DO2i) below 280-300 ml/min/m2 being associated with poor surgical outcomes.[3] At the beginning of each procedure, perfusionists wore on the chest a wireless 3-lead electrocardiogram (ECG) device (*MindWare Mobile*). After the procedure, the ECG files were analyzed in the *Kubios HRV* software to extract HRV parameters for each 3-minute time window, matching the DO2 data sampling.

Measurements:

The pre-operative risk of mortality score was calculated based on the Veteran Affair Surgical Quality Improvement Program (VASQIP) risk calculator. Patients' DO2i levels were calculated and monitored through the CDI using the following variables: pump flow, hemoglobin concentration, hemoglobin oxygen saturation, and arterial oxygen pressure. Two HRV parameters, previously validated to index perfusionists' cognitive load and stress, [4] were used: root mean square of the successive differences between heartbeats (RR) intervals (RMSSD) in ms, and low-frequency / high-frequency ratio (LF/HF ratio). LH/FH ratio has a direct relationship with cognitive load, and RMSSD has an inverse relationship with stress.

Data Analysis:

To compare the perfusionist's cognitive load in different patient perfusion conditions, based on DO2 levels, we plotted the distribution of DO2i values (each 3-minute interval) across all cases, and calculated the respective terciles, defining three groups: Low DO2i (first tercile: < 295 ml/min/m2), Medium DO2i (second tercile: 295 - 332 ml/min/m2), High DO2i (third tercile: > 332 ml/min/m2). For each 3 minutes, within each case, the patient's DO2i was classified as Low, Medium, or High. Our dataset had a hierarchical structure in which the observations in the dataset (3-min data points) were clustered within a case, and cases were clustered within perfusionists. The same perfusionists were present in multiple cases. A Generalized Linear Mixed Model (GLMM) was used to handle the non-normal distribution of the dataset and the fact that the observations (3-min data points within cases and cases within perfusionists) are dependent on each other. The model was set with fixed effects: DO2 conditions (primary predictor), 30-day mortality risk (control variable), and the interaction term between these two variables. In the GLMM, random effects were used to capture the variability within and between the levels of the random factors (i.e., perfusionists, cases, 3-min periods) and account for the potential correlation and dependency within each case and across different cases for the same perfusionist (hierarchical structure).

By including the random effects in the model, the estimated marginal means are adjusted to reflect the average response variable (i.e., RMSSD, LF/HF ratio) for each level of the predictor variable (DO2i levels), considering the variation accounted for by the random effects. Following GLMM analysis, a pairwise comparison was performed, and the p-values were adjusted using the sequential Bonferroni correction to control multiple testing. A p-value less than 0.05 was considered statistically significant for all statistical tests.

RESULTS

A total of 29 cardiac surgery patients and 4 experienced perfusionists were included in this study. Twenty-two (75.9%) patients underwent an isolated CABG procedure, 5 (17.2%) patients received an AVR procedure, and 2 (6.9%) patients had a combined CABG/AVR procedure. The GLMM analysis compared the three states (Low, Medium, and High) based on the patient perfusion condition (DO2i level) at each measurement point for perfusionists' HRV-based cognitive load and stress (Fig. 1).

Perfusionists showed significantly higher cognitive load and stress during Low DO2i conditions compared to High DO2i conditions - a higher LF/HF ratio (3.54 vs 3.00, $p = 0.033$); and a lower RMSSD (28.31 ms vs 35.58 ms, $p = 0.001$), after adjusting for patient pre-operative mortality risk. Pairwise comparison showed a significantly higher HF/LF ratio in Medium DO2i vs High DO2i conditions ($p = 0.033$), and significantly lower RMSSD in Low DO2i vs Medium DO2i conditions ($p = 0.001$). The other pairwise comparisons were not statistically significant.

DISCUSSION

This study is the first to demonstrate a relationship between patients' oxygen delivery levels as a measure of perfusion adequacy during CPB and perfusionists' cognitive load and stress indexed by objective digital biomarkers captured via a wearable sensor. The findings reveal that periods of Low DO2i (<295 ml/min/m2) are associated with significantly higher cognitive load and stress, indexed by two different HRV parameters, among perfusionists compared to periods of High DO2i (>332 ml/min/m2). Importantly, the GLMM analysis, which accounted for the nested structure of the data and patient mortality risk, showed that this relationship remained significant even after controlling for these confounders. These results suggest that maintaining adequate DO2 during CPB may not only benefit patient outcomes, as previously established [3], but may also have important implications for the cognitive performance and well-being of the perfusion team.

A particularly noteworthy finding was the differential response pattern between cognitive load and acute stress across DO2i conditions. While stress levels (indexed by decreased RMSSD) are significantly lower when DO2i reached medium levels and remained similar between Medium and High DO2i conditions, cognitive load (indexed by increased LF/HF ratio) remained elevated during Medium DO2i and only decreased significantly when DO2 reached high levels. This dissociation suggests that the cognitive demands of managing suboptimal perfusion persist even after acute stress levels are reduced, highlighting the complex relationship between physiological, psychological, and cognitive responses during

CPB management. Such findings could have important implications for understanding the cognitive neuroergonomics of perfusionists' work and for developing strategies to optimize and support both patient care and provider performance. Finally, these results highlight the potential value of incorporating perfusionist cognitive load and stress monitoring into future studies of goal-directed perfusion strategies, as these factors may represent important mediators of the relationship between perfusion management quality, perfusionists' cognitive performance, and surgical patient outcomes.

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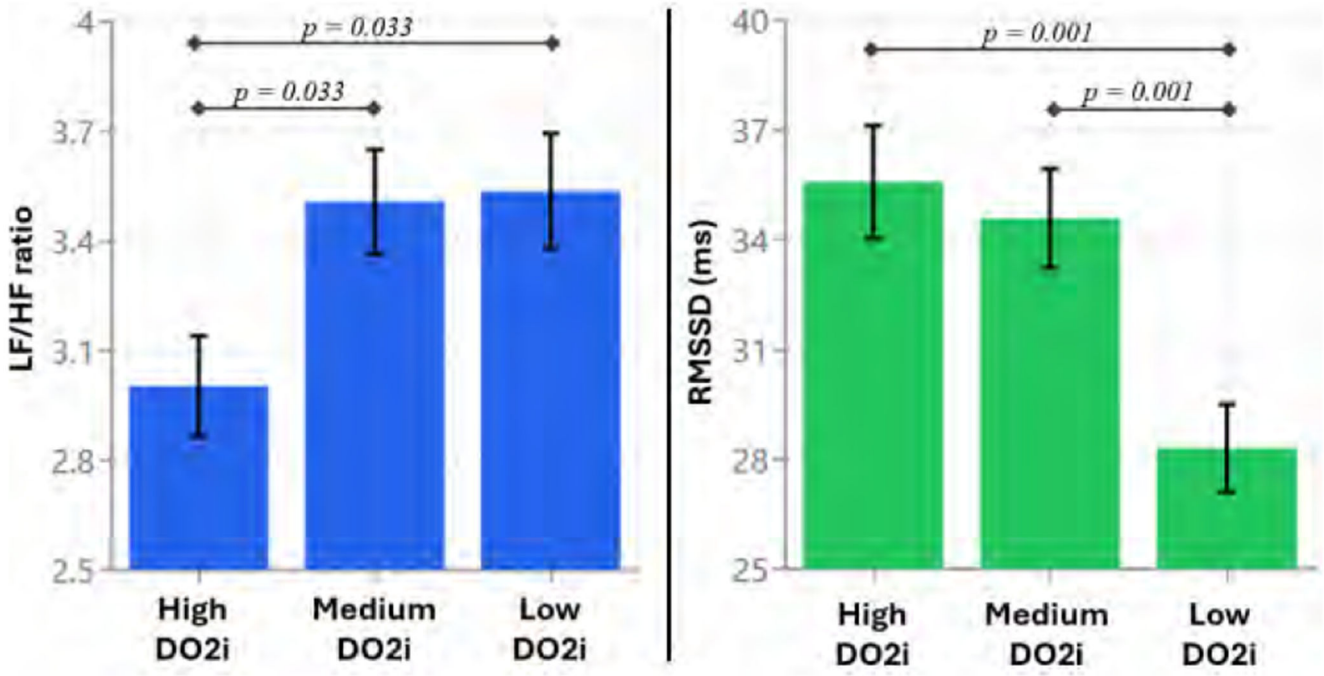

Fig. 1.

Perfusionists' HRV parameters (LF/HF ratio and RMSSD) across different patient perfusion (DO2i) conditions.