Using Digital Biomarkers for Objective Assessment of Perfusionists' Workload and Acute Stress during Cardiac Surgery

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Abstract. The cardiac operating room (OR) is a high-risk, high-stakes environment inserted into a complex socio-technical healthcare system. During cardiopulmonary bypass (CPB), the most critical phase of cardiac surgery, the perfusionist has a crucial role within the interprofessional OR team, being responsible for optimizing patient perfusion while coordinating other tasks with the surgeon, anesthesiologist, and nurses. The aim of this study was to investigate objective digital biomarkers of perfusionists' workload and stress derived from heart rate variability (HRV) metrics captured via a wearable physiological sensor in a real cardiac OR. We explored the relationships between several HRV parameters and validated self-report measures of surgical task workload (SURG-TLX) and acute stress (STAI-SF), as well as surgical processes and outcome measures. We found that the frequency-domain HRV parameter HF relative power - FFT (%) presented the strongest association with task workload (correlation coefficient:-0.491, p-value: 0.003). We also found that the time-domain HRV parameter RMSSD (ms) presented the strongest correlation with perfusionists' acute stress (correlation coefficient:-0.489, p-value: 0.005). A few workload and stress biomarkers were also associated with bypass time and patient length of stay in the hospital. The findings from this study will inform future research regarding which HRV-based biomarkers are best suited for the development of cognitive support systems capable of monitoring surgical workload and stress in real time.

Keywords: Cognitive Workload, Acute Stress, Perfusionists, Cardiac Surgery, Digital Biomarkers.

1 Introduction

The cardiac operating room (OR) is a high-risk, high-stakes environment inserted into a complex socio-technical healthcare system [1,2]. Despite the tremendous improvements in surgical patients' mortality and morbidity achieved in the past two decades, patient safety and preventable adverse event rates are still suboptimal among cardiac surgery patients [3–5]. During the cardiopulmonary bypass (CPB), the most critical phase of cardiac surgery, the perfusionist has a crucial role within the interprofessional OR team, being responsible for optimizing patient perfusion while coordinating other tasks with the surgeon, anesthesiologist, and nurses [6]. The inherently complex nature of the OR setting, alongside the requirements for effective and sustained situational awareness, decision-making, and teamwork, make perfusionists particularly vulnerable to the deleterious effects that high cognitive workload and stress may have on clinical performance [7,8].

Extensive previous literature has shown that cognitive overload and high acute stress (distress) impair surgical performance in both simulated and real-life settings [9,10]. Nonetheless, most of the existing evidence is surgeon-centered, and only a few studies have included other OR team members, particularly the perfusionists. Furthermore, the majority of this previous research has used self-report instruments (e.g., questionnaires) that provide a validated overall measure of the entire surgical procedure but do not support objective monitoring of clinicians' workload and stress in real-time [9,11].

Among several real-time objective measures, heart rate variability (HRV) is a physiological biomarker that can be unobtrusively captured via digital wearable sensors and has been used as a proxy for cognitive workload and acute stress in various settings, including the OR [9,12,13]. Through HRV analysis, many parameters are generated in the time, frequency, and non-linear domains, with each of these parameters reflecting autonomic nervous system activity (sympathetic and/or parasympathetic) at varying levels [14]. HRV has been shown to index high-level cognitive functions (e.g., cognitive workload) and emotional regulation (e.g., stress) [15].

The aim of this study was to investigate objective digital biomarkers of perfusionists' workload and stress derived from HRV metrics captured via a wearable physiological sensor in a real cardiac OR. We explored the relationships between several HRV parameters and validated self-report measures of surgical task workload and acute stress, as well as surgical processes and outcomes measures.

2 Methods

2.1 Study Setting and Design

This was an observational study conducted in the cardiac OR of a tertiary hospital in the United States between January 2021 and May 2022. The research protocol was approved by the Institutional Review Boards (IRB) at the Veterans Affairs (VA) Boston Healthcare System and Harvard Medical School. Informed consent was obtained from all participants, including patients, perfusionists, and OR staff.

2.2 Population

Participants were 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). No exclusion criteria were applied.

2.3 Procedures

At the beginning of each operation, perfusionists were attached to a wireless 3-lead electrocardiogram (ECG) device (*MindWare Mobile Impedance Cardiograph*) that records ECG signals at 500Hz. After the operation, the ECG files were exported and analyzed in the *Kubios HRV* software [16]. In *Kubios*, an automatic artifact correction was selected.

At the end of the procedure, perfusionists completed two previously validated self-report questionnaires: the Surgery Task Load Index (SURG-TLX)[17], assessing their perceived surgical task workload, and the Spielberger Short-Form State-Trait Anxiety Inventory (STAI-SF)[17,18], assessing their perceived acute stress.

2.4 Measurements

Heart Rate Variability (HRV). Perfusionists' ECG signals were processed in Kubios [16] to extract a series of 44 different HRV parameters for each 5-minute time window, calculated based on established HRV analysis guidelines [16,19]. The analysis included HRV metrics from time, frequency, and non-linear domains. To gather a measure that reflects the overall surgical procedure, the 5-minute widows were averaged across the entire procedure for each HRV parameter.

Perceived Surgical Task Workload. To measure the perceived (self-reported) workload related to the entire surgical procedure, the SURG-TLX was completed by perfusionists [17,20]. This is a 20-point scale for which the score is calculated by multiplying the number of points selected by 5 (score range: 5-100). The tool covers six different workload domains: mental demands, physical demands, temporal demands, task complexity, distractions, and situational stress. Each domain is rated individually, then averaged to generate the SURG-TLX total score.

Perceived Acute Stress. To measure the perceived (self-reported) acute stress related to the entire surgical procedure, the STAI-SF was completed by perfusionists [18]. This is a 4-point scale for which half of the items have a reverse score. The tool has six different items, asking participants to report how much they feel: calm, tense, upset, relaxed, content, and worried. Each item is rated individually, then the sum of the scores (reversed for items 1, 3, and 5) generates the STAI-SF total score, ranging from 6 to 24 points.

Surgical processes and outcome measures. Patient data was collected from the electronic health record. Surgical processes measures included: total procedure duration, cross-clamp time, and bypass time, all in minutes. Surgical outcome measures included: intrahospital mortality (%), and length of hospital stay after surgery (in days).

3 Results

A total of 37 cardiac surgery patients and 4 perfusionists were included in this study. Twenty-nine (78.4%) patients underwent an isolated CABG procedure, 5 (13.5%) patients received an isolated AVR procedure, and 3 (8.1%) patients had a combined CABG/AVR procedure. Table 1 displays the patient's demographic and surgical characteristics.

Table 1. Patient Demographic and Surgical Characteristics.

Variables	**Measures**
Sex male - *N (%)*	37 (100.0)
Age - *years*	71.0 (63.0 - 74.0)
BMI - *Kg/m2*	29.7 (27.3 - 32.5)
BSA - *m2*	2.1 (1.9 - 2.2)
Pre-Operative Risk (VASQIP risk assessment core)	
30-day Mortality Risk - *%*	0.8 (0.4 - 1.3)
30-day Morbidity Risk - *%*	6.9 (6.7 - 9.6)
30-day SSI Risk - *%*	1.4 (0.9 - 2.0)
Surgical Process and Outcome Measures	
Bypass Duration - *minutes*	112.0 (94.0 - 134.0)
Cross Clamp Time - *minutes*	71.0 (56.0 - 90.0)
Total Procedure Duration - *minutes*	330.0 (258.0 - 371.0)
Hospital Length of Stay - *days*	7.0 (6.0 - 9.0)
Mortality - *N (%)*	0 (0.0)

**BMI: body mass index; BSA: body surface area; VASQIP: Veteran Affair Surgical Quality Improvement Program; SSI: surgical site infection*

A correlation analysis was performed between all objective (HRV parameters) and subjective (self-report instruments) measures of task workload and acute stress. Table 2 (Task Workload) and Table 3 (Acute Stress) show the correlation coefficients and corresponding p-values for all statistically significant associations.

Table 2. Significant Correlations between HRV parameters and SURG-TLX total score.

HRV Parameter	HRV Domain	Correlation Coefficient	p-value
HF relative power - FFT (%)	Frequency-domain	-0.491	0.003
HF absolute power - FFT (n.u.)	Frequency-domain	-0.485	0.004
LF absolute power - FFT (n.u.)	Frequency-domain	0.485	0.004
LF relative power - FFT (%)	Frequency-domain	0.476	0.004
LF/HF ratio - FFT	Frequency-domain	0.472	0.005
VLF peak frequency - FFT (Hz)	Frequency-domain	0.454	0.007
DFA alpha1 – short-term fluctuation slope	Non-linear	0.382	0.026

**HF: high-frequency band; LF: low-frequency band; VLF: very-low-frequency band; DFA: detrended fluctuation analysis; FFT: Fast Fourier Transformation*

Table 3. Significant Correlations between HRV parameters and STAI-SF total score.

HRV Parameter	HRV Domain	Correlation Coefficient	p-value
RMSSD (ms)	Time-Domain	-0.489	0.005
SD1 in Poincaré plot (ms)	Non-linear	-0.488	0.005
HF absolute power - FFT (ms2)	Frequency-Domain	-0.485	0.006
LF peak frequency - FFT (Hz)	Frequency-Domain	-0.469	0.008
HF absolute power - FFT (log)	Frequency-Domain	-0.465	0.008
PNS index	*Kubios* Metric [16]	-0.461	0.009
RPA Lmax - maximum line length (beats)	Non-linear	0.459	0.009
VLF absolute power - FFT (ms2)	Frequency-Domain	-0.459	0.009
pNN50 (%)	Time-Domain	-0.454	0.010
TINN (ms)	Time-Domain	-0.453	0.011
SD2/SD1 ratio	Non-linear	0.436	0.014
SDNN (ms)	Time-Domain	-0.436	0.014
Total power - FFT (ms2)	Frequency-Domain	-0.434	0.015
NN50 (beats)	Time-Domain	-0.431	0.015
DFA alpha1 - short-term fluctuation slope	Non-linear	0.425	0.017
HF relative power - FFT (%)	Frequency-Domain	-0.421	0.018
HF absolute power - FFT (n.u.)	Frequency-Domain	-0.418	0.019
LF absolute power - FFT (n.u.)	Frequency-Domain	0.418	0.019
Stress index	*Kubios* Metric [16]	0.409	0.022
LF relative power - FFT (ms2)	Frequency-Domain	-0.407	0.023
RPA Shannon Entropy	Non-linear	0.401	0.026
D2 - correlation dimension	Non-linear	-0.393	0.029

LF/HF ratio - FFT	Frequency-Domain	0.391	0.030
RPA Determinism (%)	Non-linear	0.379	0.036
RPA Recurrence Rate (%)	Non-linear	0.377	0.037
HRV Triangular Index	Time-Domain	-0.369	0.041
VLF absolute power - FFT (log)	Frequency-Domain	-0.369	0.041
ApEn - Approximate Entropy	Non-linear	-0.358	0.048
SampEn - Sample Entropy	Non-linear	-0.355	0.050

**RMSSD: root mean square of the successive differences between RR intervals; SD1: standard deviation perpendicular to the line-of-identity; SD2: standard deviation along the line-of-identity; HF: high-frequency band; LF: low-frequency band; VLF: very-low-frequency band; PNS: parasympathetic nervous system activity; RPA: recurrent plot analysis; NN50:Number of successive RR interval pairs that differ more than 50 ms; pNN50:NNxx divided by the total number of RR intervals; DFA: detrended fluctuation analysis; FFT: Fast Fourier Transformation; TINN: Baseline width of the RR interval histogram; SDNN: Standard deviation of RR intervals; Stress index: Square root of Baevsky's [21] stress index.*

The scatter plots in Fig. 1 and Fig. 2 display the relationship between the HRV parameters presenting the strongest correlations with the perfusionist's workload and acute stress. Both parameters - the high-frequency (HF) band and the root mean square of the successive differences between heartbeat intervals (RMSSD) - reflect parasympathetic autonomic nervous activity (vagal modulation). However, HF is influenced by respiratory rate while RMSSD is not [22]. The inverse relationship reflects the fact that high workload and stress situations lead to a decrease in parasympathetic activity while increasing sympathetic tone.

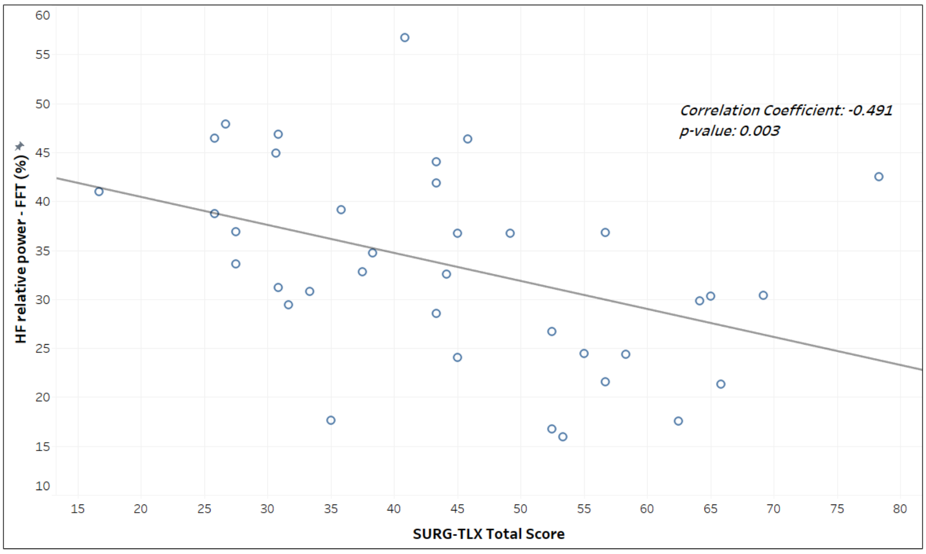

Fig. 1. Relationship between a parasympathetic-mediated HRV parameter (frequency-domain) and perfusionists' workload (SURG-TLX).

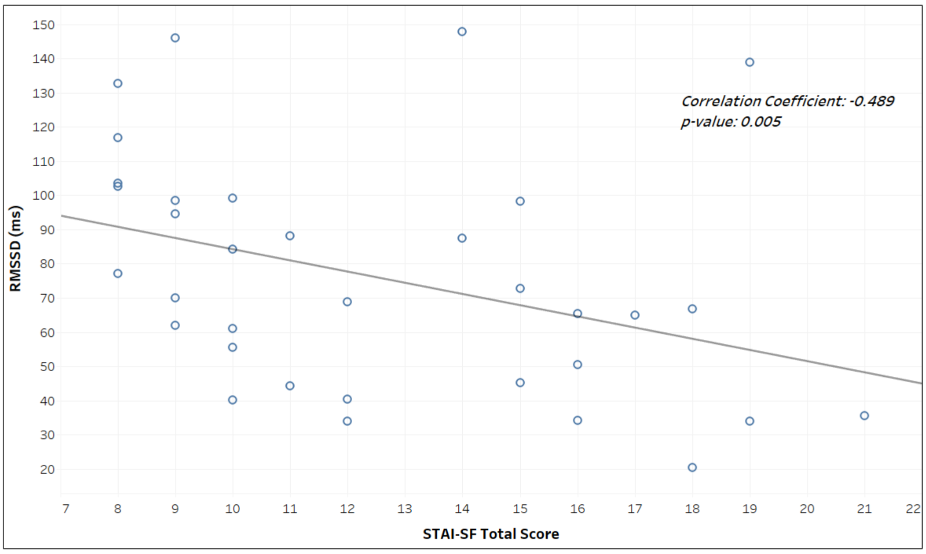

Fig. 2. Relationship between a parasympathetic-mediated HRV parameter (time-domain) and perfusionists' acute stress (STAI-SF).

The only HRV parameter associated with patient pre-operative risk scores was the very-low-frequency (VLF) relative power, which presented a correlation coefficient of -0.346, and a p-value of 0.045 with the risk for surgical site infection (SSI). No other relationships with pre-operative risk scores yielded a statistically significant correlation.

Additional correlational analysis between perfusionists' workload and acute stress metrics and surgical processes and outcome measures revealed that the bypass duration was associated with the following metrics: low-frequency (LF) absolute power (log) (correlation coefficient: 0.366, p-value: 0.033); Standard deviation along the line-of-identity (SD2) (correlation coefficient: -0.370, p-value: 0.031); Stress Index (correlation coefficient: -0.346, p-value: 0.045); and VLF absolute power (log) (correlation coefficient: -0.412, p-value: 0.016). Only the HRV parameter Mean RR-intervals (ms), which represent the mean interval between consecutive heartbeats in milliseconds, presented a statistically significant correlation with patient length of stay in the hospital after surgery (correlation coefficient: -0.346, p-value: 0.0045). No other relationships with surgical processes and outcome measures yielded a statistically significant correlation.

4 Discussion

In the present study, we collected data from patients and perfusionists in a real cardiac OR, leveraging an integrative approach based on human factors and cognitive engineering sciences [23]. To investigate objective digital biomarkers of perfusionists' workload and acute stress, we performed HRV analysis from ECG signals and explored the relationships between several HRV parameters and previously validated self-report tools. The findings from this study will inform future research regarding which HRV-based biomarkers are best suited for the development of cognitive support systems capable of monitoring surgical workload and stress in real time.

Several previous studies have assessed the cognitive workload of surgeons and, less often, other OR team members during cardiac surgery [9]. Most of these studies have used self-report instruments such as the NASA Task Load Index (NASA-TLX) [24] and, more recently, the SURG-TLX, which was validated specifically in the surgical setting [9,11]. Acute stress has also been investigated in many surgical studies, and the Spielberg STAI questionnaire is one of the most used instruments to assess acute stress in various settings [25]. Among HRV metrics, the vast majority of the studies have selected only a few parameters to investigate based on previous research [26,27]. To date, no surgical study has investigated and compared the strength of correlation among all the HRV parameters extracted in the time, frequency, and non-linear domains. Furthermore, most previous studies in the field have suggested the LF/HF ratio is the best marker of cognitive workload [9]. Nonetheless, our findings show that there are other HRV parameters with equal or even stronger correlation with SURG-TLX total score. Interestingly, our results showed that no time-domain parameter was associated with perfusionists' workload. Regarding acute stress, the strongest correlation was found with RMSSD, which corroborates previous literature that has suggested this time-domain parameter as a good indicator of acute stress [9,12]. It is also important to notice that many non-linear parameters were significantly associated with perfusionists' workload and stress, and studies exploring these parameters to infer cognitive and emotional functions in the OR are scarce. Future research should include non-linear HRV parameters in their analysis.

Surprisingly, the patient pre-operative risk, which is an indicator of expected task complexity and difficulty [28], was only associated with a few self-report items and HRV parameters. A possible explanation is that the population of patients included in this study did not substantially vary in their pre-operative risk (Table 1), therefore, not allowing the discovery of linear correlations with workload and stress. Another explanation is that high-risk patients may pose an additional workload to the surgeon, particularly in the psychomotor domain, but not necessarily to the perfusionist. The bypass duration, the time in which a heart-lung machine provides the patient perfusion, is a reliable surgical process measure that serves as a surrogate for various post-operative outcomes [29]. Several self-report and HRV parameters were associated with bypass duration, showing that a longer bypass phase is associated with a higher perfusionist's workload and stress. Length of hospital stay, an important patient outcome measure, was also moderately associated with an HRV parameter (mean R-R interval).

The findings from this study are promising, particularly as it relates to validating objective digital biomarkers of perfusionists' workload and stress that can be monitored in near or real-time during cardiac surgery. Although we have averaged the HRV parameters over the entire procedure, these metrics are extracted for each 5-minute window or even shorter, such as 1-minute, using ultra-short-term HRV analysis [30]. In the same way we currently monitor patient physiology in real-time, informing clinical decision-making in the OR, the continuous monitoring of perfusionists' cognitive and emotional states can be used by intelligent ambient systems capable of detecting cognitive overload situations and re-allocating tasks across the OR team, distributing cognitive demands [31]. Such intelligent systems [32] can also manage unavoidable interruptions to the surgical workflow, providing the surgical team with a data-driven assessment of clinicians' workload and stress that enable timely interruptions at specific moments when the workload is not highly critical [33].

Although this study reveals important relationships between perfusionists' workload, stress, and surgical processes and outcome measures, it is important to highlight that these findings cannot infer a cause-effect relationship. In fact, in the same way that task difficulty and complexity can increase cognitive load and stress, these two states can also deteriorate performance, which per se, can increase stress [34]. These relationships between task workload, acute stress, and performance are intrinsically complex and should be understood and investigated through a feedback loop perspective. Future research should attempt to model these relationships using non-linear models and network analysis in order to capture further the complexity and nuances of such a dynamic system.

5 Conclusion

In conclusion, the findings from this study provide a comprehensive exploratory analysis of the several HRV parameters that have been reported in the literature to index cognitive and emotional states across various industries in which human performance plays a critical role in safety. By investigating the comparative association between these different HRV parameters and established measures of cognitive workload and acute stress in the cardiac OR, our results advance the current scientific knowledge toward the development and validation of objective digital biomarkers of human performance in the surgical setting. More importantly, because these metrics are unobtrusively captured in real-time, our findings provide the foundational evidence for future cognitive augmentation capabilities [35] that can augment and improve performance in the OR, reducing medical errors and enhancing patient safety.

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