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Autonomic Activity and Surgical Flow Disruptions in Healthcare Providers during Cardiac Surgery

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Abstract

Cardiac surgery represents a complex sociotechnical environment relying on a combination of technical and non-technical team-based expertise. Surgical flow disruptions (SFDs) may be influenced by a variety of sources, including social, environmental, and emotional factors affecting healthcare providers (HCPs). Many of these factors can be readily observed, except for emotional factors (i.e. distress), which represents an underappreciated yet critical source of SFDs. The aim of this study was to demonstrate the sensitivity of autonomic activity metrics to detect an SFD during cardiac surgery. We integrated heart rate variability (HRV) analysis with observation-based annotations to allow data triangulation. Following a critical medication administration error by the anesthesiologist in-training, data sources were consulted to identify events precipitating this near- miss event. Using *pyphysio*, an open-source physiological signal processing package, we analyzed the attending anesthesiologists' HRV, specifically the low frequency (LF) power, high frequency (HF) power, LF/HF ratio, standard deviation of normal-to-normal (SDNN), and root mean square of the successive differences (RMSSD) as indicators of ANS activity. A heightened SNS response in the attending anesthesiologists' physiological arousal was observed as elevations in LF power and LF/HF ratio, as well as depressions in HF power, SDNN, and RMSSD prior to the near- miss event. The attending anesthesiologist subjectively confirmed a state of high distress induced by task-irrelevant environmental factors during this time. Qualitative analysis of audio/video recordings objectively revealed that the autonomic nervous system (ANS) activation detected was temporally associated with an argument over operating room management. This study confirms that it is possible to recognize detrimental psychophysiological influences in cardiac surgery procedures via advanced HRV analysis. To our knowledge, ours is the first such case demonstrating ANS activity coinciding with strong self-reported emotion during live surgery using HRV. Despite extensive experience in the cardiac OR, transient but intense emotional changes may have the potential to disrupt attention processes in even the most experienced HCP. A primary implication of this work is the possibility to detect real-time ANS activity, which could enable personalized interventions to proactively mitigate downstream adverse events. Additional studies on our large database of surgical cases are underway and new studies are actively being planned to confirm this preliminary observation.

Keywords—cardiac surgery, cognitive engineering, neuroergonomics, emotion recognition, heart rate variability

I. INTRODUCTION

Ongoing advances in sensor technology have enabled accurate estimations of underlying autonomic nervous system (ANS) activity through methods such as heart rate variability (HRV) capture and analysis [1]. ANS activity represents the interplay between the sympathetic nervous system (SNS) and parasympathetic nervous system (PNS), and changes in the balance among these systems has been shown to reflect alterations in stress [2], mental workload [3], [4], emotional status [5], self-regulatory capacity [6], [7], and more. Further, analytical approaches to quantifying HRV, including primarily time-domain and frequency-domain analyses, provide nuanced views of parasympathetic and sympathetic control [8]. Heart rate monitors capable of capturing electrocardiograms (ECGs) from users in naturalistic settings has advanced our understanding of the interactions between HRV, physiological systems, and mental state in high-risk work domains [9].

Cardiac surgery in particular represents a complex, high- consequence sociotechnical environment relying on a combination of technical and non-technical expertise in a team- based setting. Surgical flow disruptions (SFDs) to standard operating procedures may be influenced by a variety of sources, including but not limited to: patient factors (e.g. unexpected anatomy), provider expertise (e.g. novice vs. expert clinicians), provider-specific factors (e.g. fatigue), social factors (e.g. low team familiarity), environmental factors (e.g. operating room [OR] scheduling conflicts), and emotional factors (e.g. anger/frustration) [10]. Many of these sources and their impacts on cognition can be observed in healthcare providers (HCPs) through ethnographic approaches. One underappreciated yet critical source of SFDs is the influence of emotional factors, which cannot be observed without the use of either subjective self-report or objective sensors capturing underlying physiological activity.

Emotion recognition and resolution is especially important among HCPs given the known effect emotion, and distress especially, can have on processes such as perception, memory, attention, decision-making and reasoning [11]. By identifying emotional states that have the potential to disrupt cognitive processes (e.g. distress), HCPs may be better equipped to anticipate and cope with these changes. Further, the analysis of underlying physiology may provide insight into autonomic processes indicative of intense emotional changes.

The aim of this study was to demonstrate the sensitivity of autonomic activity metrics to detect a surgical flow disruption during cardiac surgery. We integrated HRV analysis with observation-based annotations to allow data triangulation.

II. METHODS

A. Data Collection

As part of a larger NIH-funded project, video, audio, and heart rate data were captured from the surgical team during a routine coronary artery bypass graft procedure (N=1). Two GoPro cameras captured a wide view of the OR and a narrow view of the surgical field. The wide view ensured insight into contextual components such as the OR layout, major equipment included, positioning and distance between HCPs, non-verbal communications among team members, and major SFDs occurring during the case. In contrast, the narrow view provided a more fine-grained snapshot of the procedure, capturing primary surgical instrumentation and equipment utilized within the sterile field. Audio data were collected via microphones equipped to the senior team members (attending anesthesiologist, attending surgeon, and primary perfusionist), capturing relevant verbal communications both inside and outside of the OR.

Team members were also each equipped with a wearable, wireless heart rate monitor (Polar H10 sensors) and a corresponding signal receiver (Polar V800). The Polar V800 device was utilized given its affordability, unobtrusiveness, and high accuracy and validity compared to traditional clinical ECG devices [12]. HRV was chosen as the primary measure of ANS activity due to its noninvasive, continuous nature of data collection, its known relationship with SNS and PNS activity, and its extensive prior utility in the surgical setting [13].

B. Case Description

Following the observation of a serious medication administration error by the resident anesthesiologist (new trainee), which should have been prevented with oversight from the senior anesthesiologist, multiple data sources were consulted to identify the events precipitating this near-miss event. Data sources consulted included those utilized in the study design initially (audio, video, and physiological recordings), as well as additional information gained from institutional and systemic investigations into the near-miss event.

Specifically, a routine root cause analysis was carried out by hospital administrators [14], which uncovered a self-reported incidence of transient anger/frustration experienced by the senior anesthesiologist. This was induced by task-irrelevant environmental factors concerning OR management, requiring the anesthesiologist to leave the OR and negotiate a departmental argument, all occurring prior to the near-miss event. Audio analysis confirms the timing of the departmental argument outside of the OR, while video analysis confirms that at the time of the medication administration error, the attending anesthesiologist was in the OR and resuming task-relevant teaching and patient care duties.

C. Data Analysis

Using *pyphysio*, an open-source physiological signal processing Python package [15], we analyzed the attending anesthesiologists' HRV to detect the influence of ANS activity via SNS activation and PNS withdrawal, and thereby emotional distress, contributing to the lack of situation awareness and expected oversight during the resident's improper medication administration. Data were analyzed from the time of first incision through sternal closure by calculating HRV values for all consecutive non-overlapping one-minute segments. HRV values from all of the one-minute segments during the course of the case were also averaged, to visualize and quantify the attending anesthesiologists' deviation from their average value over time.

Specific HRV components considered included both frequency-domain and time-domain calculations. In the frequency domain, we considered the low frequency (LF) power, high frequency (HF) power, and the ratio between the two (LF/HF ratio). Physiological inputs contributing to LF power, or the relative power of the low-frequency band (0.04- 0.5 Hz), include both sympathetic and parasympathetic influences, as well as the baroreflex [16]. Prior research has generally considered the LF power band to be most closely related to sympathetic activation, though given the variety of inputs represented by the LF power value, this component can be difficult to interpret. However, HF power, the relative power of the high-frequency band (0.15–0.4 Hz), is known to be directly reflective of parasympathetic control and the respiratory sinus arrhythmia (RSA). Finally, the LF/HF ratio can be derived easily when these values are known. The LF/HF ratio therefore reflects the proportion of both sympathetic and parasympathetic innervation [17] such that higher values tend to indicate sympathetic predominance and arousal, while lower values indicate sympathetic withdrawal. HF power and the LF/HF ratio have been previously associated with mental workload states on short time scales [18]. Based on short-term HRV data collected from a sample of over 1,200 healthy individuals aged 45-54, an average expected LF/HF ratio under resting conditions is around 2.01 units [19]. This value is our frame of reference for the subsequent analysis, given that the attending anesthesiologists' age at the time of data collection was 47.

Additional analysis considered components in the time domain, including the root mean square of the successive differences (RMSSD) and the standard deviation of normal-to-normal peaks (SDNN). RMSSD has been shown to be strongly associated with cognitive load [8], and given the primarily PNS tone reflected by RMSSD, lower values indicate parasympathetic predominance and lower arousal states. SDNN similarly has an inverse relationship with states of arousal, and is primarily mediated by the parasympathetic RSA in short-term analyses [8]. According to the ELSA-Brasil study [19], the average expected RMSSD value under resting conditions for individuals from ages 45-54 is around 30 milliseconds (ms), while the average expected SDNN value is around 41.6 ms.

Reports given during root cause analysis procedures and audio data during the case were consulted to provide additional contextual information as necessary.

III. RESULTS

A. Physiological Results

Upon initial visual inspection, HRV results revealed support for extreme SNS activation and PNS withdrawal in consultation with both time-domain and frequency-domain parameters corresponding to the time prior to the near-miss event. In particular, the attending anesthesiologists' LF power was notably elevated amid a 30-minute span of data fluctuating minimally around their average value. The two notable peaks in LF power observed in Fig. 1a represent 42% and 35% increases in LF power compared to the average value calculated over the course of the surgery.

As expected, the HF power trend revealed similar findings, indicating extreme PNS withdrawal during the same time period. The two notable decreases in HF power seen in Fig. 1b correspond to 16% and 37% decreases in HF power compared to the attending anesthesiologists' average of all one-minute segments over the course of the surgery.

Heightened SNS activation, reflecting an extreme elevation in the attending anesthesiologists' physiological arousal was also quantified as an LF/HF ratio value of 3.39 units, which can be observed in Fig. 1c. Considering the attending anesthesiologists' average LF/HF ratio value over the surgery (2.01 units), this single segment, representing one minute in time, represents a 69% increase in LF/HF ratio. This peak is also drastically higher than surrounding values within a 30-minute time span.

Analysis of the parasympathetic tone through time-domain analyses revealed a sharp decrease in RMSSD (Fig. 2a) as well as SDNN (Fig. 2b) amid the same set of samples reported above. In particular, while the average RMSSD value across the duration of the case was 12.4 ms, the decrease in RMSSD observed represents a 25% reduction in RMSSD in that segment. Similarly, the decrease in SDNN observed corresponds to a 37% reduction from the average SDNN value of 30.4 ms.

B. Self-Report Results

During standard root cause analysis procedure following the case, the attending anesthesiologist confirmed a state of high emotional distress (specifically, frustration and anger) induced by task-irrelevant environmental factors. Meanwhile, the trainee who committed the medication administration error confirmed lack of procedural knowledge and had no prior experience in the cardiovascular OR. In combination, it could be argued that the trainee's inexperience coincided with the senior anesthesiologists' lapse in attention/judgment, ultimately resulting in the preventable near-miss event that occurred.

The anesthesiologists' self-reported state of distress was further confirmed by audio recordings capturing an argument over OR management occurring at the same time as the LF power and LF/HF ratio elevation, as well as the decline in HF power, RMSSD, and SDNN values. This involved conflicting demands stemming from a discussion surrounding OR management and flow. The nature of the discussion required staff to compromise on OR flow and created tension among staff given the limited resources available (OR rooms currently in use and scheduled for use), patient concerns (delaying surgeries for patients who were already prepared and waiting for surgery), timing (operating late into the night), and personal concerns (one clinician was pregnant at the time).

IV. DISCUSSION

This preliminary study confirms the feasibility of recognizing detrimental psychophysiological influences during cardiac surgery procedures via HRV analysis, complemented by procedural, contextual, and self-report data sources. To our knowledge, this is the first such case demonstrating ANS activity coinciding with strong self-reported emotion during naturalistic surgery using HRV. The primary finding of this analysis suggests that despite HCP's extensive experience in the cardiac OR, transient but intense ANS activity (represented through a variety of validated HRV features indicative of SNS activation and PNS withdrawal) corresponding to self-reported emotional distress may have the potential to disrupt attention processes in even the most qualified of clinicians.

Though the underlying physiological processes and inputs determining the LF/HF ratio are debatable, we can say with more certainty that parasympathetic activation contributes to this specific observation, given the corresponding decrease in HF power when considered in isolation. During the same timeframe, we can also observe a corresponding increase in LF power in isolation, which may represent sympathetic, parasympathetic, and/or baroreflex inputs [8]. Findings representing similar changes by approaching the data through time-domain analysis further corroborate these patterns. Specifically, RMSSD and SDNN calculations lend support to the role of parasympathetic withdrawal during the course of the extraneous argument observed.

The influence of emotional states on a range of cognitive processes [11] and decision-making is well-described [20], [21], yet investigation into its effects in surgery are underexplored. The operative environment is a uniquely data-rich setting equipped with devices automatically capturing a wide range of information regarding patient status, surgery-specific procedures, temporal relationships, and more. Additionally, the OR affords the opportunity for granular team-based, behavioral, technical, and non-technical analysis of the surgical team. It is possible, but not yet common practice, to simultaneously collect physiological data of HCPs in this setting as well. Harnessing these disparate data sources alongside one another in a time- synchronized, continuous fashion allows a more comprehensive exploration and understanding of internal, otherwise unobservable factors influencing surgical processes.

A direct extension of this work in future research involves sharing HRV status to users in real time, lending to heightened emotional awareness and the opportunity to intervene appropriately. In particular, future work could enable personalized cognitive engineering coping interventions to proactively mitigate downstream adverse events [22]. Additional studies on our large database of surgical cases are underway to confirm this preliminary observation and explore these interactions further.

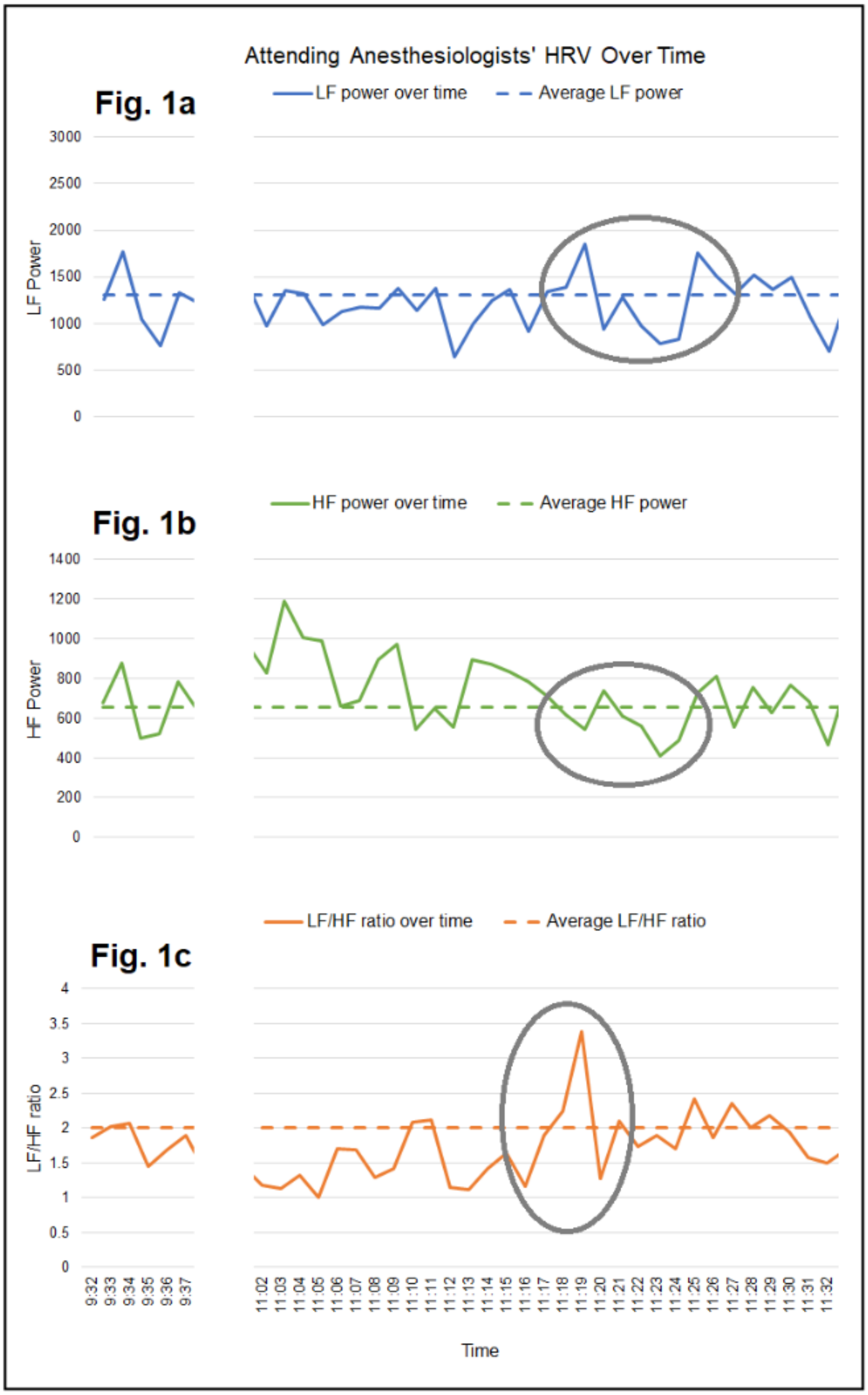

Fig. 1. Visual representation of the attending anesthesiologist's 1a) LF power, 1b) HF power, and 1c) LF/HF ratio over time. For reference, the dotted line in each panel indicates this individual's average value over the course of the entire surgical procedure. From 11:12:27 through 11:26:47, the anesthesiologist is engaged in a frustrating case-irrelevant conversation. The marked elevation in SNS activity, observed here through peaks in LF power and uncharacteristically high LF/HF ratio value, as well as the noted PNS withdrawal, observed here as decreases in HF power, may be an indicator of emotional distress, and possibly of anger.

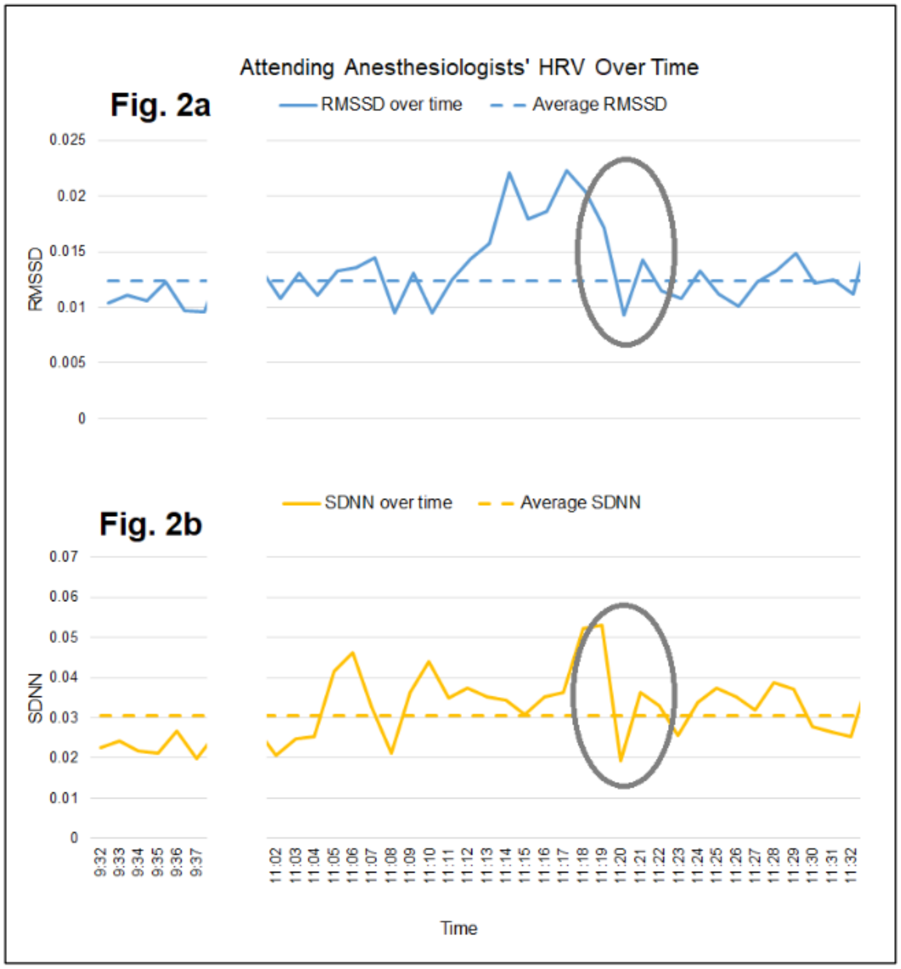

Fig. 2. Visual representation of the attending anesthesiologist's 2a) RMSSD and 2b) SDNN over time. The dotted line in each panel indicates the average value recorded over the course of the entire surgery. Corresponding to the time of the self-reported frustrating case-irrelevant conversation, we can observe a decrease in PNS activity (a sharp decline in RMSSD and in SDNN), complementing results from the frequency-domain analysis.

REFERENCES

[1] U. R. Acharya, K. P. Joseph, N. Kannathal, C. M. Lim, and J. S. Suri, "Heart rate variability: A review," *Med. Biol. Eng. Comput.*, vol. 44, no. 12, pp. 1031–1051, 2006.

[2] H.-G. Kim, E.-J. Cheon, D.-S. Bai, Y. H. Lee, and B.-H. Koo, "Stress and Heart Rate Variability: A Meta-Analysis and Review of the Literature," *Psychiatry Investig.*, vol. 15, no. 3, pp. 235–245, 2018.

[3] A. M. Hughes, G. M. Hancock, S. L. Marlow, K. Stowers, and E. Salas, "Cardiac Measures of Cognitive Workload: A Meta-Analysis," *Hum. Factors J. Hum. Factors Ergon. Soc.*, no. March, p. 001872081983055, 2019.

[4] D. McDuff, S. Gontarek, and R. Picard, "Remote measurement of cognitive stress via heart rate variability," in *2014 36th Annual International Conference of the IEEE Engineering in Medicine and Biology Society*, 2014, pp. 2957–2960.

[5] A. Dzedzickis, A. Kaklauskas, and V. Bucinskas, "Human emotion recognition: Review of sensors and methods," *Sensors (Switzerland)*, vol. 20, no. 3, 2020.

[6] R. McCraty and F. Shaffer, "Heart rate variability: New perspectives on physiological mechanisms, assessment of self-regulatory capacity, and health risk," *Glob. Adv. Heal. Med.*, vol. 4, no. 1, pp. 46–61, 2015.

[7] S. C. Segerstrom and L. S. Nes, "Heart rate variability reflects self- regulatory strength, effort, and fatigue," *Psychol. Sci.*, vol. 18, no. 3, pp. 275–281, 2007.

[8] F. Shaffer and J. P. Ginsberg, "An Overview of Heart Rate Variability Metrics and Norms," *Front. Public Heal.*, vol. 5, no. September, pp. 1– 17, 2017.

[9] S. E. Frazier and S. H. Parker, "Measurement of physiological responses to acute stress in multiple occupations: A systematic review and implications for front line healthcare providers," *Transl. Behav. Med.*, vol. 9, pp. 158–166, 2019.

[10] D. A. Wiegmann, A. W. Elbardissi, J. A. Dearani, R. C. Daly, and T. M. S. Iii, "Disruptions in surgical flow and their relationship to surgical errors: An exploratory investigation," *Surgery*, vol. 142, no. 5, pp. 658– 665, 2007.

[11] V. R. LeBlanc, M. M. McConnell, and S. D. Monteiro, "Predictable chaos: A review of the effects of emotions on attention, memory and decision making," *Adv. Heal. Sci. Educ.*, vol. 20, no. 1, pp. 265–282, 2014.

[12] D. Giles, N. Draper, and W. Neil, "Validity of the Polar V800 heart rate monitor to measure RR intervals at rest," *Eur. J. Appl. Physiol.*, vol. 116, no. 3, pp. 563–571, 2016.

[13] R. D. Dias, M. C. Ngo-Howard, M. T. Boskovski, M. A. Zenati, and S. J. Yule, "Systematic review of measurement tools to assess surgeons' intraoperative cognitive workload," *Br. J. Surg.*, vol. 105, no. 5, pp. 491– 501, 2018.

[14] A. W. Wu, A. K. M. Lipshutz, and P. J. Pronovost, "Effectiveness and Efficiency of Root Cause Analysis in Medicine," *JAMA*, vol. 299, no. 6, pp. 685–687, 2008.

[15] A. Bizzego, A. Battisti, G. Gabrieli, G. Esposito, and C. Furlanello, “pyphysio: A physiological signal processing library for data science approaches in physiology,” *SoftwareX*, vol. 10, 2019.

[16] F. Shaffer, R. McCraty, and C. L. Zerr, “A healthy heart is not a metronome: An integrative review of the heart’s anatomy and heart rate variability,” *Front. Psychol.*, vol. 5, no. September, pp. 1–19, 2014.

[17] Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology, “Heart rate variability: Standards of measurement, physiological interpretation and clinical use,” *Eur. Heart J.*, vol. 17, pp. 354–381, 1996.

[18] R. Castaldo, P. Melillo, U. Bracale, M. Caserta, M. Triassi, and L. Pecchia, “Acute mental stress assessment via short term HRV analysis in healthy adults: A systematic review with meta-analysis,” *Biomed. Signal Process. Control*, vol. 18, pp. 370–377, 2015.

[19] E. M. Dantas *et al.*, “Reference values for short-term resting-state heart rate variability in healthy adults: Results from the Brazilian Longitudinal Study of Adult Health—ELSA-Brasil study,” *Psychophysiology*, vol. 55, no. 6, 2018.

[20] K. L. Mosier and U. Fischer, “The Role of Affect in Naturalistic Decision Making,” *J. Cogn. Eng. Decis. Mak.*, vol. 4, no. 3, pp. 240–255, 2010.

[21] Y. Albayram, M. M. H. Khan, T. Jensen, R. Buck, and E. Coman, “The effects of risk and role on users’ anticipated emotions in safety-critical systems,” *EPCE 2018*, pp. 369–388, 2018.

[22] M. A. Zenati, L. Kennedy-Metz, and R. D. Dias, “Cognitive Engineering to Improve Patient Safety and Outcomes in Cardiothoracic Surgery,” *Semin. Thorac. Cardiovasc. Surg.*, pp. 1–7, 2019.