Quantifying Intraoperative Team Cognitive Workload in Complex Surgical Environments*

Lauren R. Kennedy-Metz, Roger D. Dias, Heather M. Conboy, Jacob Nudel, Eileen M. Stock and Marco A. Zenati

Abstract—**Preventable adverse events continue to occur in surgery. Non-invasive psychophysiological measures, such as heart rate variability (HRV) objectively indicate cognitive workload of surgical team members. We investigated cognitive workload states via HRV analysis during real-life cardiac surgeries.**

I. Introduction

Medical error is the third-leading cause of preventable death in the U.S. [1]; intraoperative errors are especially frequent and consequential [2]. Since up to 50% of medical errors and resulting adverse events are preventable [3], it is critical to investigate novel interventions to enhance surgical safety.

Individual and team performance in surgery can become easily compromised as cognitive workload increases, creating the potential to adversely affect non-technical skills, most notably, situation awareness [4]. The cardiac surgery operating room (OR) is a particularly appealing domain because of its high risk and the added layer of cross-disciplinary team dynamics.

This study presents preliminary analysis investigating the relationship between cognitive workload of three cardiac team members (attending surgeon, attending anesthesiologist, primary perfusionist) and surgical phases during aortic valve replacement (AVR) and coronary artery bypass graft (CABG) surgeries at a tertiary academic hospital.

Across surgical phases, we expected to see a distribution of cognitive workload levels, depending on duties of the team member(s) primarily involved. Across individual roles, we anticipated certain phases to present similar levels of cognitive workload, particularly those involving close communication and coordination among all team members.

II. Methods

A. Data Collection

This project received approval from the Harvard Medical School and Veterans Affairs Boston Healthcare System's Institutional Review Boards. Informed consent was obtained from all patients (N=34), and every healthcare provider present in the OR during recordings (N=93).

Data were collected during real-life AVR and CABG procedures in the cardiac OR (N=34 cases) between 2017 and 2018. Two GoPro cameras were used for video recordings (narrow and wide views), three Sony recorders were used for audio (one device per team member), heart rate was collected using wireless Polar H10 chest monitors (one monitor per team member), and a modified SURG-TLX [5] was used for nine self-reported measures of cognitive workload (one per team member for pre-, during, and post-bypass phases).

B. Data Analysis

Audio, video, and psychophysiological recordings were manually time synced by one author (LKM). Data were analyzed from the patient arrival until the end of sternal closure. Identification and annotation of surgical phases was done manually by one author (LKM), according to previously developed standardized process models of AVR and CABG procedures [6], resulting in thirteen surgical phases.

Primary analysis of psychophysiological data relied on a well-established time-domain measure of HRV, the root mean square of the successive differences (RMSSD), known to reflect vagally-mediated activity and cognitive workload [7]. Analysis involved a subset of the complete dataset, including nine total cases (four CABG, five AVR). Statistical analysis was conducted using SPSS statistical software, and significance is reported at $P<0.05$.

III. Results

A mixed model ANOVA with Surgical Phase as the between-subject factor and Provider Role as the within-subjects factor revealed significant differences ($F(12,60)=2.814$, $P=0.024$). Primary findings are reported below as (mean ± standard deviation, P-value) (Figure 1).

A. Surgical Phase

Tukey post hoc tests showed that during pre-induction, anesthesiologists experienced higher cognitive workload compared to perfusionists (15.15 ms ± 3.00 ms vs. 20.68 ms ± 0.98 ms respectively; P=0.024). During anesthesia induction, cognitive workload was significantly higher among anesthesiologists (15.32 ms ± 2.77 ms) compared to both surgeons (20.94 ms ± 0.94 ms, P=0.025) and perfusionists (21.56 ms ± 1.19 ms, P=0.011).

During anastomoses and aortotomy/valve replacement phases, our data show that surgeons (10.19 ms ± 2.24 ms) experienced higher cognitive workload compared to perfusionists (20.59 ms ± 6.39 ms, P=0.045). Finally, surgeons (11.19 ms ± 1.55 ms) experienced higher cognitive

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L. R. Kennedy-Metz and M. A. Zenati are affiliated with the Medical Robotics & Computer-Assisted Surgery (MRCAS) Lab, Harvard Medical School, Boston, MA 02115 (corresponding author phone: 857-203-6397; fax: 857-203-5608; e-mail: Lauren.Kennedy-Metz@va.gov).

R. D. Dias is affiliated with the STRATUS Center for Medical Simulation. H. M, Conboy with the University of Massachusetts at Amherst, J. Nudel with Boston Medical Center, and Eileen Stock with the Cooperative Studies Program, Department of Veterans Affairs, Perry Point, MD.

workload compared to perfusionists (20.71 ms ± 5.09 ms, P=0.029) during separation from bypass.

B. *Provider Role*

Tukey post hoc tests comparing different phases across individual roles reveal significant simple main effects for anesthesiologists and surgeons. Notable differences within anesthesiologists include significantly lower cognitive workload experienced during aortic clamp and cardioplegia (20.15 ms ± 2.28 ms) and anastomoses or aortotomy (18.62 ms ± 1.54 ms) phases compared to heparinization (15.73 ms ± 3.47 ms), aortic cannulation (17.06 ms ± 2.00 ms), and separation from bypass (16.62 ms ± 1.59 ms), among others. Surgeons, on the other hand, experienced significantly higher cognitive workload levels during aortic clamp and cardioplegia (10.45 ms ± 1.90 ms), anastomoses or aortotomy (10.19 ms ± 2.24 ms), and separation from bypass (11.19 ms ± 1.55 ms) compared to pre-induction (19.83 ms ± 1.58 ms), anesthesia induction (20.94 ms ± 0.94 ms), and sterile prepping (19.78 ms ± 0.25 ms) phases (P<0.05 in all cases).

IV. DISCUSSION

As hypothesized, cognitive workload levels varied according to provider role and surgical phase, with role-specific phases associated with specific higher levels of cognitive workload (e.g. anesthesia induction). Also, within surgeons specifically, the first three phases were characterized by significantly lower cognitive workload, according to RMSSD values, compared to primarily surgical tasks later in the procedure, supporting the expected phase-specific differences within provider roles.

Additionally, certain phases known to require team communication and coordination induced similar levels of cognitive workload across provider roles. For example, during pre-incision time-out and sternotomy phases, results reveal the narrowest range in RMSSD values across all three team members (0.8 ms during pre-incision time-out and 0.9 ms during sternotomy). This indicates high psychophysiological synchrony, which is absent during other phases of the surgeries. Previous work has shown the advantage of synchronous cognitive workload states in completing complex tasks in ambiguous situations [8].

Granular data on cognitive workload measures could assist in guiding analysis of events post hoc, supplementing approaches such as root cause analysis, as has been previously reported and guide interventions to mitigate the risk of errors [9]. Future work involves integrating providers' cognitive workload states into an automated, context-aware support system to facilitate optimal individual and team situation awareness and, subsequently, performance in real time. Additional future work will investigate a more fine-grained temporal relationship between states of cognitive workload and meaningful events, aimed at establishing causality, allowing for predictive analytics.

REFERENCES

[1] M. A. Makary and M. Daniel, "Medical error — the third leading cause of death in the US," *Br. Med. J.*, vol. 353, pp. 1–5, 2016.

[2] J. A. Wahr, R. L. Prager, J. H. Abernathy III, E. A. Martinez, E. Salas, P. C. Seifert, R. C. Groom, B. D. Spiess, B. E. Searles, T. M. Sundt III, J. A. Sanchez, S. A. Shappell, M. H. Culig, E. H. Lazzara, D. C. Fitzgerald, V. H. Thourani, P. Eghtesady, J. S. Ikonomidis, M. R. England, F. W. Sellke, and N. A. Nussmeier, "Patient safety in the cardiac operating room: Human factors and teamwork: A scientific statement from the american heart association," *Circulation*, vol. 128, no. 10, pp. 1139–1169, 2013.

[3] A. P. Gurses, G. Kim, E. A. Martinez, J. Marsteller, L. Bauer, L. H. Lubomski, P. J. Pronovost, and D. Thompson, "Identifying and categorising patient safety hazards in cardiovascular operating rooms using an interdisciplinary approach: A multisite study," *BMJ Qual. Saf.*, vol. 21, no. 10, pp. 810–818, 2012.

[4] K. Vande Walle and C. Greenberg, "Intraoperative non-technical skills: A critical target for improving surgical outcomes," *BMJ Qual. Saf.*, vol. 27, no. 2, pp. 99–101, 2018.

[5] M. R. Wilson, J. M. Poolton, N. Malhotra, K. Ngo, E. Bright, and R. S. W. Masters, "Development and validation of a surgical workload measure: The surgery task load index (SURG-TLX)," *World J. Surg.*, vol. 35, no. 9, pp. 1961–1969, 2011.

[6] G. S. Avrunin, S. C. Christov, L. A. Clarke, H. M. Conboy, J. Leon, and M. A. Zenati, "Process Driven Guidance for Complex Surgical Procedures."

[7] S. Laborde, E. Mosley, and J. F. Thayer, "Heart rate variability and cardiac vagal tone in psychophysiological research - Recommendations for experiment planning, data analysis, and data reporting," *Front. Psychol.*, vol. 8, no. FEB, pp. 1–18, 2017.

[8] R. Stevens, T. Galloway, D. Halpin, and A. Willemsen-Dunlap, "Healthcare teams neurodynamically reorganize when resolving uncertainty," *Entropy*, vol. 18, no. 12, pp. 1–15, 2016.

[9] M. A. Zenati, K. Leissner, S. Zorca, L. Kennedy-Metz, S. Yule, and R. D. Dias, "First Reported Use of Team Cognitive Workload for Root Cause Analysis in Cardiac Surgery," *Semin. Thorac. Cardiovasc. Surg.*, no. 4, pp. 1–3, 2018.

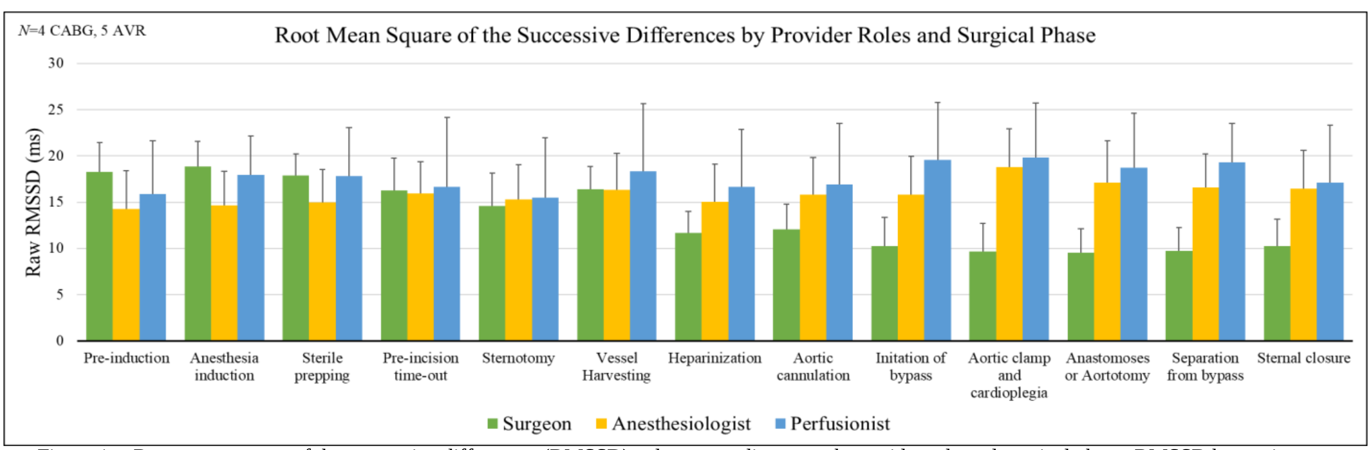

Figure 1. Root mean square of the successive differences (RMSSD) values according to each provider role and surgical phase. RMSSD has an inverse relationship with cognitive workload, such that higher RMSSD values reflect lower states of workload. Data are reprsented as means and standard deviations. The Vessel Harvesting phase is unique to CABG, and the Post-Operative Debriefing phase has been excluded from these analyses.