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Original Article

Team-level heart rate variability dispersion across surgical stages of coronary artery bypass grafting procedures

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ABSTRACT

The operating room is a safety-critical environment where effective teamwork is essential to patient safety. In the cardiac operating room, heart rate variability (HRV) offers a noninvasive window into psychophysiological activity of providers that may provide insight into team-level physiological responses in this safety-critical context. In this exploratory study, team-level HRV dispersion of surgical teams during coronary artery bypass grafting (CABG) procedures was assessed using HRV metrics from the time-domain, frequency-domain, and nonlinear domain. Data from 15 CABG procedures and surgical teams were used to derive team-level HRV dispersion values for each surgical team and procedure stage, then analyzed using repeated-measures ANOVA to determine whether HRV dispersion varied significantly across stages. CABG procedures were analyzed using the original 14-stage segmentation and a condensed 8-stage segmentation for sensitivity analysis. The original segmentation served as the primary framework, with the condensed segmentation as a sensitivity analysis. Time-domain (SDNN) and log-transformed frequency-domain (HF) dispersion differed significantly across CABG stages under both segmentation schemes, whereas nonlinear domain (SampEn) dispersion did not show statistically significant stage effects. Holm-adjusted post hoc pairwise comparisons for SDNN did not identify significant differences between stages. In contrast, HF dispersion was significantly higher during closure than during selected earlier stages under both segmentations of the CABG procedures. These findings indicate stage-related variation in team-level SDNN and HF dispersion during CABG and support further investigation of HRV dispersion as a physiological measure in surgical team research.

1. Introduction

The surgical operating room is a safety-critical environment in which effective teamwork is essential to patient safety. Teamwork evolves across distinct stages of a surgical procedure. As teamwork shifts across surgical phases, tracking these changes over the course of a surgical procedure is essential (Hull et al., 2011; Moreal et al., 2026). Conventional approaches to assessing teamwork, however, often provide static or retrospective evaluations that may not capture these temporal changes. Physiological measures are being explored as a complementary data stream for understanding teamwork as it unfolds during surgical procedures.

From a human factors perspective, the potential value of physiological measures lies in their ability to provide continuous, quantitative information during ongoing tasks without disrupting performance (Awtry et al., 2025). While physiological measures do not provide a direct assessment of teamwork, they can complement behavioral and subjective measures by providing additional information that can be examined in relation to changes in procedural demands.

This measurement challenge aligns with concerns raised a decade ago at the Human Factors and Ergonomics Society's 59th Annual Meeting, at a session titled "*What will Quantitative Measures of Teamwork Look Like in 10 years?*" (Salas et al., 2015). At that session, teamwork scholars recognized the challenges of measuring teamwork and called for new theories and methods aligned with the dynamic nature of team interactions. Responding to this need, a growing body of research is examining physiological measures as tools for examining team dynamics (Gorman et al., 2010; Kazi et al., 2021; Khalid et al., 2027; Stevens et al.,

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2017).

Kozlowski and Ilgen (2006) define *teamwork* as the interaction between two or more individuals who share one or more common goal(s), perform contextually relevant tasks, exhibit interdependencies in relation to their workflow, goals, and outcomes, and have different roles and responsibilities. Understanding teamwork in safety-critical environments, such as the surgical operating room, is particularly important because effective teamwork contributes to patient safety (Hughes et al., 2016; Rosen et al., 2015). Broadly, adverse events in surgical settings have also been associated with teamwork and coordination failures, further emphasizing the importance of understanding team functioning in the operating room (Catchpole et al., 2008; Helmreich & Schaefer, 1994).

Given the importance of teamwork in the operating room, researchers have explored the potential of heart rate variability for understanding team functioning. *Heart rate variability (HRV)*, defined as variation in time intervals between heartbeats (Besson et al., 2025) has been used to examine physiological responses at the individual level. Individual HRV has been used in research examining variables such as attention, stress, and cognitive workload (e.g., Hughes et al., 2019; Kim et al., 2018; The et al., 2020). More recently, research has extended HRV beyond individual-level applications to explore team-level physiological measures, including physiological synchrony, which refers to the temporal coupling in physiological activity between two or more individuals (Palumbo et al., 2017; Wespi et al., 2025). Building on this broader work, the present study focuses on team-level HRV dispersion across surgical stages. Unlike physiological synchrony, team-level HRV dispersion does not assess whether physiological signals change together over time; rather, it reflects variability in the minute-level HRV observations contributed by team members within a surgical stage.

Team functioning changes over time as members coordinate their activities in response to evolving task demands and contextual pressures (Coultas et al., 2014; Kozlowski, 2015; Marks et al., 2001). Coordinated team functioning does not require team members to experience identical demands or exhibit identical individual states. In functionally differentiated teams, such as surgical teams, members contribute to a common task through distinct yet interdependent roles, and the demands placed on individual members may therefore differ at the same point in time. As Hutchins (1995) illustrated in the cockpit, coordinated system performance can rely on differentiated contributions across members rather than identical activity among team members. Similarly, members of a cardiac surgical team may experience different task demands within the same procedural stage while contributing to a common team objective. Variability in physiological observations within the team may therefore provide descriptive information about how physiological activity differs during a given procedural stage.

Although HRV is conceptualized at the individual level, individual physiological measures may be summarized at the team level when the aggregation approach is conceptually aligned with the team-level construct being examined (Kozlowski, 2015; Nijstad et al., 2025). In the present study, aggregation follows a dispersion-based approach because cardiac surgical teams are functionally differentiated systems in which members perform distinct but interdependent roles. As such, dispersion may provide a descriptive way to characterize the variability in physiological observations within the team-stage period.

1.1. Coronary artery bypass grafting (CABG) procedure

The coronary artery bypass grafting procedure prolongs life, helps relieve chest pain (i.e., angina) and reduces the risk of myocardial infarction (Bachar & Manna, 2023). The procedure involves creating a new route for blood to flow around blocked coronary arteries in the heart using healthy blood vessels (or "conduits") harvested from another part of the body. This restored blood flow helps improve cardiac function and prevents further ischemic damage. CABG is a commonly performed major cardiac surgical procedure, with almost 400,000 performed each year in the U.S. alone (Bachar & Manna, 2023). CABG is performed by a highly trained surgical team of 8–12 individuals, including cardiac-thoracic surgeons, anesthesiologists, nurses, surgical technicians, and perfusionists (Bachar & Manna, 2023). The distinct yet interdependent responsibilities of these team members create substantial coordination demands throughout the procedure.

1.2. Heart rate variability (HRV)

While *heart rate* provides a snapshot of how fast the heart is beating at a given moment, *heart rate variability* refers to variation in time intervals between consecutive heartbeats (Berntson et al., 1997; Besson et al., 2025). HRV reflects variation in cardiac activity influenced by autonomic regulation (Sacha, 2014). HRV can be examined using time-domain, frequency-domain, and nonlinear approaches (Table 1; Sammito et al., 2024; Shaffer & Ginsberg, 2017; Task Force of the European Society of Cardiology & the North American Society of Pacing & Electrophysiology, 1996).

Time-domain analysis examines variation in intervals between successive normal heartbeats (NN intervals; Billman, 2011). Standard deviation of NN Intervals (SDNN) was selected as the time-domain metric because it has been previously used to examine HRV across key intraoperative performance points in surgical research (De Louche et al., 2024; Laborde et al., 2017). *Frequency-domain analysis* examines the distribution of HRV within specific frequency ranges (Billman, 2011). High-frequency (HF) power was selected as the frequency-domain measure because it captures variability within the high-frequency band and is commonly interpreted in relation to parasympathetic influences on heart rate (Laborde et al., 2017).

Nonlinear domain includes methods used to characterize complex and nonperiodic properties of the heart-rate signal (Shaffer & Ginsberg, 2017). Unlike time- and frequency-domain methods, which summarize the magnitude and frequency composition of variability, nonlinear methods are designed to evaluate a chaotic, irregular, and adaptive nature of HRV. Through examining HRV using nonlinear methods, insights can be ascertained regarding the underlying regulatory mechanisms of the autonomic nervous system. Sample Entropy (SampEn) was selected as a complementary nonlinear measure to capture features of HRV not represented by time- or frequency-domain measures.

The three metrics (i.e., SDNN, HF, and SampEn) capture complementary information across HRV domains while aiming to minimize redundancy among the measures. SDNN provides a broader index of R-R interval variability across the recording period and, as mentioned, it has been used previously in intraoperative surgical research (De Louche et al., 2024; Laborde et al., 2017). For example, RMSSD, another time-domain measure, was not selected because it is highly correlated with HF, which would increase overlap between the selected time- and frequency-domain measures (Laborde et al., 2017).

HF was used as the frequency-domain measure because its

Table 1
Heart rate variability metrics examined in the present study.

Domain	Metric	Description
Time-Domain	SDNN	Standard deviation of normal-to-normal interbeat intervals; reflects overall heart rate variability influenced by sympathetic and parasympathetic influences
Frequency-Domain	HF power	Quantifies heart rate variability within the high-frequency band (0.15–0.4 Hz); commonly associated with parasympathetic influences on heart rate
Nonlinear	SampEn	Reflects the degree of regularity or irregularity in the sequence of cardiac intervals over time

Note. There are additional HRV metrics in the time-, frequency-, and nonlinear domains; only metrics examined in the present study are presented in this table. Descriptions were derived from Shaffer and Ginsberg (2017) and Sammito and colleagues (2024).

physiological interpretation is more specifically associated with parasympathetic influences than, for example, LF, which reflects contributions from both sympathetic and parasympathetic activity (Sammito et al., 2024). Other frequency-domain measures (e.g., LF/HF) were not used because the ratio does not correspond clearly to a single autonomic process (Sammito et al., 2024). Finally, SampEn was used as the nonlinear measure because it describes the regularity of intervals between heartbeats, providing information that differs from the time- and frequency-domain measures. Alternative nonlinear approaches (e.g., SD1 and SD2) were not selected because some capture different properties of the signal that overlap with SDNN (Sammito et al., 2024). The metrics selected provide a complementary representation of the three HRV domains (i.e., time-, frequency-, and nonlinear domains) rather than to suggest that SDNN, HF, and SampEn are universally preferred over other HRV metrics.

In this study, team-level HRV dispersion is examined as an exploratory physiological measure that may help characterize how physiological activity within the team varies across procedural stages. This variation may be relevant to differences in workload or task demands experienced across members of the surgical team. Team-level HRV dispersion characterizes variability in the minute-level HRV observations contributed by the representative team members within a given stage; it may therefore help describe differences in physiological activity across stages with varying procedural demands. However, these patterns should not be interpreted as direct evidence of a shared workload, cognitive, emotional, or motivational state without further investigation. Establishing whether team-level HRV dispersion is meaningfully related to a particular team state would require additional validation using independent measures, such as workload assessments or behavioral observations, and performance outcomes.

Despite growing interest in physiological measures for understanding team functioning, relatively few studies have explored physiological measures aggregated at the team level, particularly in the operating room. Even less is known about whether team-level HRV dispersion varies across changing task contexts, including the distinct stages of a surgical procedure. The present study addresses this gap by examining team-level HRV dispersion across stages of coronary artery bypass grafting procedures. Characterizing this stage-related variation represents an initial step toward determining whether this team-level physiological measure may be useful in future research examining dynamic surgical team processes. As such, this study sought to answer the following research question: *Does team-level heart rate variability dispersion vary across stages of CABG procedures?*

1.3. Current research

The following exploratory hypotheses were examined:

Hypothesis 1. Time-domain (SDNN) dispersion will differ significantly across surgical stages.

Hypothesis 2. Frequency-domain (HF) dispersion will differ significantly across surgical stages.

Hypothesis 3. Nonlinear domain (SampEn) dispersion will differ significantly across surgical stages.

2. Method

The objective was to examine whether team-level HRV dispersion differed across surgical stages. Archival data from an Institutional Review Board (IRB) approved research project (approval 3296; granted on July 7, 2020; see Kennedy-Metz et al., 2024) were used for this research, which complied with all relevant ethical standards. All participants provided written informed consent prior to participation.

2.1. Design

2.1.1. Participants

For each CABG procedure, HRV data were collected from the attending surgeon, attending anesthesiologist, primary perfusionist, and scrub nurse. The clinicians occupying these roles varied across procedures. Some clinicians participated in more than one procedure; however, team composition was not identical across cases. These roles were selected as primary representatives of the four core cardiac surgery subteams (i.e., cardiac surgery, anesthesia, perfusion, and nursing), each of which includes multiple clinicians. The team-level HRV dispersion examined in this study reflects variability in HRV observations contributed by these four representative roles rather than physiological observations from every individual present in the operating room. Participants were not instructed to follow a specific diet (e.g., avoid caffeine consumption), follow a particular sleep routine, or avoid certain medications (e.g., beta blockers). Individual demographic information was not available in the archival dataset used for this study.

2.1.2. CABG stages

The present study used a convenience sample of 15 CABG procedures drawn from an archival series of cardiac surgical cases. For all 15 procedures, the final hospital disposition was documented as "discharged." CABG procedures were conceptualized using two segmentations: a 14-stage structure and an 8-stage structure (Table 2). Hereafter, the 14 stages will be referred to as the "original" CABG segmentation, and the 8 stages as the "condensed" CABG segmentation. The original segmentation was based on Dias and colleagues' (2021) conceptualization of 14 discrete stages, whereas recent work has represented CABG procedures using 8 broader stages (Kennedy-Metz et al., 2024). The condensed segmentation was examined as a sensitivity analysis to determine whether the observed findings were similar when the same CABG procedures were represented using a broader stage framework.

Procedural events were marked during the surgeries by a researcher using Video Sync Pro software, and procedural recordings were then reviewed to verify the timing of the annotated events and make corrections when needed. These event timestamps were used to define the boundaries of the CABG stages outlined by Dias and colleagues (2021), while the same procedures were grouped into the broader 8-stage framework for the condensed segmentation. Stage duration was calculated from the elapsed time between annotated stage boundaries (Table 4).

Table 2
Mapping of original (14-Stage) and condensed (8-Stage) CABG segmentations.

14-Stage "Original" CABG	8-Stage "Condensed" CABG
Stage 1: Pre-Induction	Stage 1: Preparation and Induction
Stage 2: Anesthesia Induction	
Stage 3: Sterile Prepping	Stage 2: Opening
Stage 4: Pre-Incision Time Out	
Stage 5: Sternotomy	
Stage 6: Vessel Harvesting	Stage 3: Prebypass Preparation
Stage 7: Heparinization	
Stage 8: Cannulation	
Stage 9: Initiate Cardiopulmonary Bypass (CPB)	Stage 4: Initiate Bypass & Arrest Heart
Stage 10: Clamp Aorta & Cardioplegia	
Stage 11: Anastomoses	Stage 5: Anastomoses
Stage 12: Separate from Bypass	Stage 6: Weaning from Bypass
Stage 13: Sternal Closure	Stage 7: Closure
Stage 14: Postoperative Debriefing	Stage 8: Postoperative

Note. The original segmentation represents the 14-stage CABG framework, whereas the condensed segmentation combines the same procedures into 8 broader stages. The condensed segmentation was examined as a sensitivity analysis to assess whether findings were similar when the procedures were represented using a broader stage framework.

2.2. HRV processing

Team members were equipped with a 3-lead ambulatory electrocardiogram (ECG) monitor (Fig. 1; MindWare Mobile Impedance Cardiograph; MindWare Technologies) to capture ECG waveforms for subsequent HRV analysis at a sampling rate of 500 Hz. ECG data were processed using Kubios HRV Premium (Tarvainen et al., 2014) to obtain HRV measures for each team member. Processing used the smooth-priors detrending method ($\lambda = 500$) and an interpolation rate of 4 Hz. Frequency bands were defined as very low frequency (VLF; 0–0.04 Hz), low frequency (LF; 0.04–0.15 Hz), and high frequency (HF; 0.15–0.40 Hz). Time-varying analyses used a 300-s window with a 60-s grid interval, providing HRV estimates at one-minute intervals; frequency-domain analyses used a 300-s window with 50% overlap. For SampEn, the embedding dimension was 2 and the tolerance was 0.2 x SD. Time-stamped procedural annotations were used to align the HRV observations with the corresponding CABG stages.

The present analyses focused on minute-level SDNN, HF, and SampEn values. ECG data processed using Kubios HRV Premium were used to obtain minute-level values for SDNN, HF power, and SampEn for each of the four representative surgical team members. Kubios-derived HRV values were exported and organized in separate spreadsheets for each surgical team. The minute-level observations were then aligned with the corresponding CABG stage boundaries based on the procedural timestamps. Therefore, within each team, HRV observations for the attending surgeon, attending anesthesiologist, primary perfusionist, and scrub nurse were assigned to the surgical stage during which they occurred.

2.3. Handling of missing data

Prior to statistical analysis, all HRV metrics were screened for missingness. R was used to handle missing data. Missingness was assessed separately for each HRV metric (i.e., SDNN, HF, and SampEn) across each surgical stage within each team. Known sources of missingness included delays in turning on participants' monitors and device issues/malfunctions during ECG signal recording. Missingness was summarized by HRV metric, surgical stage, and team for both segmentations.

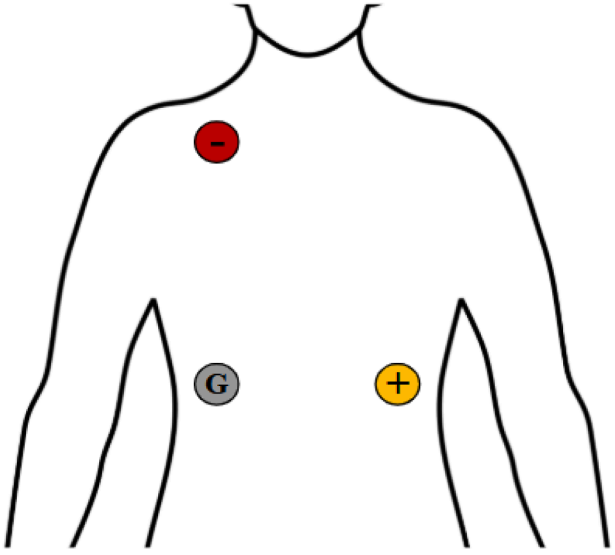


Fig. 1. 3-Lead ECG electrode placement.
Note. Schematic of the three-electrode MindWare ECG configuration. - and + indicate the negative and positive ECG recording electrodes, respectively; G indicates the ground electrode. Adapted from Wikimedia Commons (Wallroth, 2026).

Stage 14 (from the original segmentation) and Stage 8 (from the condensed segmentation) were excluded from the inferential analyses because these stages contained substantial missingness, including cases in which no HRV data were available across all metrics for individual participants. For the remaining missingness in Stages 1–13 (of the original segmentation) and Stages 1–7 (of the condensed segmentation), Multiple Imputation by Chained Equations (MICE) with Predictive Mean Matching (PMM) was used for imputation (van Buuren & Groothuis-Oudshoorn, 2011). For each segmentation, 30 imputed datasets were generated using 20 iterations. PMM generated replacement values by identifying observed cases with similar predicted values and drawing imputations from observed donor values.

The imputation models included surgical stage, participant identity within the team, and the other HRV measures as predictors. More specifically, SDNN was predicted from surgical stage, participant identity, HF, and SampEn; HF was predicted from surgical stage, participant identity, SDNN, and SampEn; and SampEn was predicted from surgical stage, participant identity, SDNN, and HF. Surgical stage and participant identity were included as categorical predictors but were not themselves imputed.

Imputation diagnostics included descriptive comparisons of the means, standard deviations, and ranges of the original observed values and imputed replacement values, which were broadly comparable. Multiple imputation was only used for missing values; all valid observed values were used in their original form. Additional details regarding the handling of missing data are provided in the Supplemental Materials (Tables S1-S5). Multiple imputation was conducted in R using the *mice* package (van Buuren & Groothuis-Oudshoorn, 2011).

2.4. Team-level HRV dispersion

Team-level HRV dispersion was operationalized as the stage-level dispersion in minute-level HRV observations contributed by the four representative team members. Within each surgical stage and team, the minute-level HRV observations from the four representative roles were combined and the standard deviation was calculated separately within each completed dataset. The resulting dispersion estimates were then averaged to produce one final dispersion score for each team-stage combination and HRV metric. The resulting values represented overall dispersion of HRV observations within the team-stage period, with lower values indicating less variability and higher values indicating greater variability. The minimum possible dispersion value is 0, indicating no variability among the HRV observations within the team-stage period, and there is no theoretical maximum. As dispersion is calculated as a standard deviation, it is expressed on the same measurement scale as the corresponding HRV metric.

2.5. Data screening & statistical analyses

A power analysis (Cohen, 1988) was conducted using G*Power 3.1.9.7 (Faul et al., 2007) to determine the minimum sample size required to detect small ($f = 0.10$), medium ($f = 0.25$), and large ($f = 0.40$) effects in repeated-measures ANOVAs. To address the research question and examine the exploratory hypotheses, six repeated-measures ANOVAs were conducted: SDNN dispersion, log-transformed HF dispersion, and SampEn dispersion for both segmentations. Analyses were conducted in Jamovi (The jamovi project, 2025).

Prior to inferential analysis, the assumptions for repeated-measures ANOVAs were evaluated, including the normality of the model residuals and sphericity of the repeated-measures factor. Residual Q-Q plots were examined for each dispersion outcome. HF dispersion showed some departure from normality, particularly in the upper tail, and was therefore log-transformed prior to inferential analysis for both segmentations. Examination of the residual Q-Q plots following transformation indicated improved conformity with the normality

assumption. SDNN and SampEn dispersion scores were analyzed on their original scales. Residual Q-Q plots comparing untransformed and log-transformed HF dispersion are provided in the Supplemental Materials (Figures S1 and S2).

Sphericity was assessed using Mauchly's test, and Greenhouse-Geisser corrections were applied where sphericity was violated. Following significant omnibus effects, pairwise comparisons were conducted using Holm-adjusted *p*-values. Given the exploratory nature of the study, no additional adjustment was applied across the six omnibus tests, and the omnibus *p*-values were interpreted as exploratory rather than confirmatory. Alpha was set at .05 for the statistical significance threshold.

3. Results

The results of the six repeated-measures ANOVAs are summarized in Table 3. The omnibus *p*-values are interpreted as exploratory rather than confirmatory. Holm adjustments were retained for post hoc pairwise comparisons following significant omnibus tests. The condensed segmentation represents a sensitivity analysis of the same CABG procedures rather than an independent replication. Stage-specific means, standard deviations, and 95% confidence intervals for all three HRV dispersion metrics under both segmentations are provided in the Supplemental Materials (Tables S6-S7).

Stage durations varied across CABG procedures. Descriptive statistics for the duration of each stage in the original and condensed segmentations are presented in Table 4. For each stage, the mean, standard deviation, minimum, and maximum duration were calculated across the 15 procedures.

3.1. Time-domain: SDNN original CABG (Adjusted to 13 stages)

A repeated-measures ANOVA was conducted to examine differences in time-domain (SDNN) dispersion across the original surgical stages. Mauchly's test indicated that the assumption of sphericity had been violated, $W = 7.81 \times 10^{-8}$, $p < .001$. Therefore, degrees of freedom were corrected using the Greenhouse-Geisser estimate of sphericity ($\varepsilon = .28$). The analysis found a statistically significant effect of surgical stage on SDNN dispersion, $F(3.34, 46.78) = 4.71$, $p = .005$, partial $\eta^2 = .25$. Consistent with Hypothesis 1, an overall stage effect on SDNN dispersion was observed. Given the significant omnibus stage effect, post hoc Holm-adjusted pairwise comparisons were conducted to examine differences between individual stages. No pairwise comparisons were statistically significant after Holm adjustment, indicating that the omnibus stage effect did not identify specific pairs of stages that differed significantly.

3.2. Frequency-domain: HF original CABG (Adjusted to 13 stages)

A repeated-measures ANOVA was performed to examine differences in log-transformed HF dispersion across the original surgical stages. Mauchly's test indicated that the assumption of sphericity had been violated, $W = 4.52 \times 10^{-8}$, $p < .001$. Therefore, degrees of freedom were corrected using the Greenhouse–Geisser estimate of sphericity ($\varepsilon = .30$). The results showed that the effect of the surgical stage on log-transformed HF dispersion was statistically significant, $F(3.64, 50.99) = 5.51$, $p = .001$, partial $\eta^2 = .28$. Consistent with Hypothesis 2, an overall stage effect on log-transformed HF dispersion was observed. Given the significant omnibus stage effect, post hoc Holm-adjusted pairwise comparisons were conducted to examine differences between individual stages. Holm-adjusted pairwise comparisons found a statistically significant difference between Stage 1 and Stage 13, $t(14) = -4.33$, $p_{holm} = .04$, as well as between Stage 4 and Stage 13, $t(14) = -5.43$, $p_{holm} = .007$. No other pairwise comparisons were statistically significant after Holm adjustment.

Table 3
Hypotheses and results summary.

Hypotheses	Result for Original CABG	Results for Condensed CABG
H1: Time-domain (SDNN) dispersion will differ significantly across surgical stages.	Stage effect observed	Stage effect observed
H2: Frequency-domain (HF) dispersion will differ significantly across surgical stages.	Stage effect observed	Stage effect observed
H3: Nonlinear domain (SampEn) dispersion will differ significantly across surgical stages.	No stage effect observed	No stage effect observed

Note. HF dispersion was log-transformed prior to inferential analyses based on distributional diagnostics. SDNN and SampEn dispersion were analyzed on their original scales.

3.3. Nonlinear domain: SampEn original CABG (Adjusted to 13 stages)

A repeated-measures ANOVA was performed to examine differences in SampEn dispersion across the original surgical stages. Mauchly's test indicated that the assumption of sphericity had been violated, $W = 5.61 \times 10^{-8}$, $p < .001$. Therefore, degrees of freedom were corrected using the Greenhouse–Geisser estimate of sphericity ($\varepsilon = .34$). The results showed that the effect of surgical stage on SampEn dispersion was not statistically significant, $F(4.13, 57.85) = 0.54$, $p = .71$, partial $\eta^2 = .04$. An overall stage effect on SampEn dispersion was not observed; therefore, the pattern anticipated in Hypothesis 3 was not evident in these data.

3.4. Time-domain: SDNN condensed CABG (Adjusted to 7 stages)

A repeated-measures ANOVA was conducted to examine differences in SDNN dispersion across the condensed surgical stages. Mauchly's test indicated that the assumption of sphericity had been violated, $W = 0.01$, $p < .001$. Therefore, degrees of freedom were corrected using the Greenhouse–Geisser estimate of sphericity ($\varepsilon = .39$). The results found a statistically significant effect of surgical stage on SDNN dispersion, $F(2.36, 33.00) = 5.51$, $p = .006$, partial $\eta^2 = .28$. Consistent with Hypothesis 1, an overall stage effect on SDNN dispersion was observed in the condensed segmentation. Given the significant omnibus stage effect, post hoc Holm-adjusted pairwise comparisons were conducted to examine differences between individual stages. No pairwise comparisons were statistically significant after Holm adjustment, indicating that the omnibus stage effect did not identify specific pairs of stages that differed significantly.

3.5. Frequency-domain: HF condensed CABG (Adjusted to 7 stages)

A repeated-measures ANOVA was performed to examine differences in log-transformed HF dispersion across the condensed surgical stages. Mauchly's test indicated that the assumption of sphericity had been violated, $W = 0.01$, $p < .001$. Therefore, degrees of freedom were corrected using the Greenhouse–Geisser estimate of sphericity ($\varepsilon = .44$). The results showed that the effect of surgical stage on log-transformed HF dispersion was statistically significant, $F(2.63, 36.84) = 4.23$, $p = .01$, partial $\eta^2 = .23$. Consistent with Hypothesis 2, an overall stage effect on log-transformed HF dispersion was observed in the condensed segmentation. Holm-adjusted post hoc pairwise comparisons indicated statistically significant differences between Stage 1 and Stage 7, $t(14) = -4.03$, $p_{holm} = .03$, and between Stage 2 and Stage 7, $t(14) = -5.01$, $p_{holm} = .004$. Log-transformed HF dispersion was higher at Stage 7 than at Stages 1 and 2. No other pairwise comparisons were statistically significant after Holm adjustment.

3.6. Nonlinear domain: SampEn condensed CABG (Adjusted to 7 stages)

A repeated-measures ANOVA was performed to examine differences in nonlinear SampEn dispersion across the condensed surgical stages.

Table 4
Descriptive statistics for CABG stage duration across the original and condensed segmentations.

Original CABG	*M*	*SD*	Min	Max	Condensed CABG	*M*	*SD*	Min	Max
Stage 1: Pre-Induction	30.4	13	11.5	57.0	Stage 1: Preparation and Induction	74.6	18.6	36.1	104
Stage 2: Anesthesia Induction	44.2	14.6	15.3	69.7					
Stage 3: Sterile Prepping	38.6	7.15	26.0	54.6	Stage 2: Opening	47.5	6.92	35.0	59.6
Stage 4: Pre-Incision Time Out	0.76	0.27	0.42	1.42					
Stage 5: Sternotomy	8.19	3.62	3.15	16.8					
Stage 6: Vessel Harvesting	73.6	14.0	58.6	114	Stage 3: Prebypass Preparation	130	32.0	95.1	216
Stage 7: Heparinization	25.0	18.6	12.3	78.4					
Stage 8: Cannulation	31.4	14.9	16.2	65.7					
Stage 9: Initiate Cardiopulmonary Bypass (CPB)	1.42	0.51	0.77	2.45	Stage 4: Initiate Bypass & Arrest Heart	5.55	1.53	3.80	9.00
Stage 10: Clamp Aorta & Cardioplegia	4.13	1.37	2.80	7.30					
Stage 11: Anastomoses	86.3	35.4	37.1	143	Stage 5: Anastomoses	86.3	35.4	37.1	143
Stage 12: Separate from Bypass	22.8	13.0	7.00	64.7	Stage 6: Weaning from Bypass	22.8	13.0	7.00	64.7
Stage 13: Sternal Closure	44.4	18.3	30.4	105	Stage 7: Closure	44.4	18.3	30.4	105

Note. $N = 15$. Duration is reported in minutes. Condensed-stage durations were calculated at the procedural level by summing the durations of the corresponding original stages, and descriptive statistics were then calculated across procedures. Therefore, condensed-stage standard deviations, minima, and maxima do not necessarily equal the sum of the corresponding original-stage values. Excluded stages (i.e., stage 14 of the original segmentation and stage 8 of the condensed segmentation) are not reported because they were excluded from the subsequent HRV analyses.

Mauchly's test indicated that the assumption of sphericity had been violated, $W = 0.36$, $p = .008$. Therefore, degrees of freedom were corrected using the Greenhouse–Geisser estimate of sphericity ($\varepsilon = .55$). The results showed that the effect of surgical stage on SampEn dispersion was not statistically significant, $F(3.29, 46.05) = 0.23$, $p = .89$, partial $\eta^2 = .02$. An overall stage effect on SampEn dispersion was not observed; therefore, the pattern anticipated in Hypothesis 3 was not evident in the condensed segmentation.

4. Discussion

The present study examined whether team-level HRV dispersion, operationalized using time-, frequency-, and nonlinear domain HRV metrics, varied across the distinct stages of the CABG procedure. Across both segmentations, statistically significant stage effects were observed for time-domain (SDNN) and log-transformed frequency-domain (HF) dispersion, whereas nonlinear domain (SampEn) dispersion did not show a statistically significant stage effect.

4.1. Time-domain (SDNN)

Statistically significant stage effects for SDNN dispersion were observed in both stage segmentations with moderate effect sizes. These results indicated that the degree of physiological dispersion varied across surgical stages. A similar overall stage-related SDNN effect was observed under both stage segmentations. However, the lack of significant post hoc pairwise differences after Holm correction suggests that the analyses did not identify specific pairs of stages that differed significantly from one another. Therefore, although the omnibus tests indicated overall stage effects, the present analyses do not establish which specific stages differed in SDNN dispersion.

HRV has been regarded as a "surrogate parameter" of how the brain and cardiovascular system interact with each other (Ernst, 2017). This perspective is grounded in the understanding that HRV reflects the dynamic influence of the autonomic nervous system, particularly the balance between sympathetic and parasympathetic activity, on cardiac function. According to the neurovisceral integration model, this balance is shaped by neural circuits that govern cognitive control, attention regulation, and emotional stability (Forte et al., 2019). At the team level, however, the interpretation of HRV dispersion remains exploratory. Changes in SDNN dispersion across surgical stages may be related to differences in team members' physiological activity in response to changing procedural demands. Higher SDNN dispersion in some stages could be consistent with functional role differentiation, in which each team member draws on specialized expertise to perform distinct tasks. Differences in individual physiological patterns may also arise due to attentional focus or motor activity across roles. The mechanisms underlying the observed dispersion were not directly assessed in the present study.

4.2. Frequency-domain (Log-Transformed HF)

Log-transformed HF showed statistically significant stage effects under both segmentations. Holm-adjusted post hoc comparisons also identified specific stage differences. Under the original segmentation, log-transformed HF dispersion was significantly higher at Stage 13 (Sternal Closure) than at Stages 1 (Pre-Induction) and 4 (Pre-Incision Time Out). Under the condensed segmentation, log-transformed HF dispersion was significantly higher at Stage 7 (Closure) than during Stages 1 (Preparation and Induction) and 2 (Opening). Together, both segmentations showed greater HF dispersion during closure relative to selected earlier procedural stages.

HF reflects variation in cardiac activity within the high-frequency range and is commonly associated with parasympathetic influences on the heart rate (Laborde et al., 2017). However, in the present study, the outcome represents dispersion in stage-level HF observations across team members rather than the absolute HF level of any individual clinician. Therefore, greater dispersion observed during closure may reflect increasing heterogeneity in physiological activity across team members during this stage. Differences in role-specific tasks and responsibilities may contribute to these patterns; however, these processes were not examined in the present study and should be investigated in future work. Additionally, interpretation of the HF findings should also consider the potential influence of respiration. While respiration was not measured in this study, differences in breathing patterns may have contributed to the observed HF dispersion.

4.3. Nonlinear (SampEn)

SampEn, which captures the complexity and unpredictability of interbeat intervals, did not show a statistically significant stage effect under either segmentation. One possible explanation is that SampEn dispersion may be less responsive to the procedural differences captured by the stage segmentations used in this study. However, this explanation was not directly assessed, and the present findings do not establish why SampEn dispersion did not vary significantly across stages.

Differences among HRV metrics may depend on several factors such as the characteristics of the physiological signal, recording duration, and task context. In the present analyses, SDNN dispersion and log-transformed HF dispersion showed a stage-related effect whereas SampEn dispersion did not. Despite these differences, the study was not designed to determine *why* these metrics differed in their responsiveness

to the surgical stage. Future work could examine factors such as segment duration, analytic parameters, and task characteristics to better understand differences in the sensitivity of HRV dispersion measures across procedural stages.

4.4. Limitations

As with all measurement approaches, HRV has its strengths and weaknesses. While it offers unobtrusive insights into autonomic nervous system activity, it should not be interpreted as a standalone diagnostic tool. HRV cannot, by itself, diagnose teamwork quality, nor should it be treated as a definitive measure of performance without complementary contextual support. Lower team-level HRV dispersion does not necessarily indicate optimal team performance, and conversely, effective teamwork may occur across varying levels of HRV dispersion.

A fundamental challenge of using physiological measurement for team research is establishing a precise theoretical link between individual physiological data and the team-level states being inferred (Hill et al., 2014). While certain shared events (e.g., the team responding to a medical emergency the patient is experiencing during the procedure) may evoke similar physiological changes across members, many team contexts involve heterogeneous roles and responsibilities. Team members may be attending to different stimuli, engaging in different cognitive tasks, and regulating stress in different ways. Thus, patterns of physiological similarity or variability may arise for reasons unrelated to teaming.

From a methodological standpoint, the operationalization of team-level HRV dispersion in this study is agnostic to *why* that dispersion exists. Research recommends "triangulation" (i.e., using multiple types of data such as self-reports, behavioral observations, and physiological measures) to enhance validity by using different measures to study the same construct (Hill et al., 2014). This approach is also consistent with prior surgical HRV research, in which HRV has commonly been used alongside other measures rather than as a standalone measure (The et al., 2020).

Furthermore, the current study analyzed data from only four roles (i.e., surgeon, anesthesiologist, perfusionist, and scrub nurse), meaning team-level HRV dispersion values do not reflect the entire surgical team, such as physician assistants and circulating nurses. The composition of the roles included in the dispersion calculation may also influence the observed values; a different combination of team members may exhibit a different pattern of HRV dispersion. The primary outcome aggregated observations across these representative roles, which limits the ability to determine whether particular clinical roles contributed disproportionately to the observed stage-related dispersion patterns.

Additionally, limitations related to the archival nature of the data carry risk for generalizability. This includes the small sample size and lack of definitive demographic variables. Detailed case-level clinical characteristics, including surgical urgency, patient acuity, procedural complexity, intraoperative events, and complications, were not available for the present analysis. Such factors may influence clinicians' physiological responses and could contribute to variation in team-level HRV dispersion. Another limitation is that some clinicians participated in multiple CABG procedures. Therefore, observations across cases were not fully independent at the personnel level. This dependence was not modeled separately. Future work with larger sample sizes can account for repeated clinician participation across cases. Another limitation is that imputation cannot fully replace physiological information that was not obtained, and missingness may therefore introduce uncertainty into the findings.

Furthermore, HRV data are sensitive to individual and contextual factors, such as physical activity, alcohol consumption, and smoking, which can enhance or suppress HRV (Quintana et al., 2016; Sammito et al., 2024). Physical activity and posture were also not measured in the present study, and these factors may have differed across surgical roles and stages (e.g., the surgeon may experience different movement and task demands as compared to the scrub nurse). As a result, some of the observed team-level HRV dispersion may reflect role-specific physical activity in addition to other physiological responses. Future research incorporating measures of movement or posture may help distinguish these influences. Additionally, environmental and occupational exposures (e.g., noise, extreme temperatures, contact with harmful substances) can also modulate HRV through their impact on the autonomic nervous system (Sammito et al., 2024). Although these exposures were not examined in the present study, they represent additional factors that may contribute to variability in HRV across surgical team members.

4.5. Implications for research and practice

Future work should examine the relationship between team-level HRV dispersion and observed team states or processes to establish whether physiological dispersion corresponds with meaningful aspects of team functioning. Although the present study identified statistically significant stage effects for SDNN dispersion and HF dispersion, the practical or clinical significance of these effects remains unknown. Accordingly, these findings should be interpreted as exploratory, and the relationship between HRV dispersion and team functioning requires further validation against directly observed team processes. Such validation may help determine whether particular magnitudes or changes in HRV dispersion have practical relevance for surgical teamwork, training, performance, or safety.

Despite the increasing availability of physiological measurement tools, integrating them into practice remains complicated. Careful attention must be paid to the timing of data collection, sampling methods, and theoretical validity of physiological markers (Gorman et al., 2025; Kazi et al., 2021; Khalid et al., 2027). This work contributes to exploring physiological approaches to studying teamwork in safety-critical environments where errors carry significant consequences. The method explored here may inform future tools that are scientifically valid and operationally feasible, helping bridge the gap between research and application. Additionally, this approach may contribute to future research on dynamic team states by examining physiological variation alongside other measures of team functioning, thereby addressing concerns about the static treatment of dynamic team constructs (Fyhn et al., 2023; Rapp et al., 2021). However, careful interpretation is essential when using physiological indicators or aggregating individual responses into team-level conclusions.

The team-level HRV dispersion measure examined in this study is not currently intended for clinical monitoring, performance evaluation, or real-time decision support. At this stage, its potential applications are more appropriately situated within research and training. For example, future studies could pair HRV dispersion with video-based behavioral coding or other independent measures of communication, coordination, and workload to examine whether physiological dispersion corresponds with observable team processes. Such findings may also help identify procedural phases that warrant closer examination in simulation or training, particularly when physiological measures are considered alongside independent indicators of task demands or team functioning.

Future work can determine whether the observed patterns in SDNN and HF dispersion are unique to CABG or generalize to other surgical procedures and non-surgical domains. The finding that HF dispersion was greater during closure than during selected earlier procedural stages across both segmentations identifies closure as a potentially informative period for more focused investigation. Mixed-effects models could also be used to account for repeated clinicians across procedures, team-level clustering, repeated observations across surgical stages, and stage-level covariates such as duration.

Role-specific HRV trajectories should also be examined alongside team-level dispersion to determine whether particular clinical roles systematically contribute to observed stage-related patterns. Continuous temporal synchrony methods (e.g., sliding-window cross-correlations, computational modeling) may further help capture transient

fluctuations in the relationships among team members' physiological signals. Such approaches would complement the present dispersion-based measure by examining whether team members' physiological activity changes together over time, rather than only assessing the degree to which their HRV values differ within a given stage. Such patterns may be useful for identifying short-lived physiological coupling around procedural transitions or periods of changing task demands and, in future validation studies, examining whether those patterns correspond with observed team processes.

5. Conclusion

A decade after the question "*What will Quantitative Measures of Teamwork Look Like in 10 years?*" (Salas et al., 2015), this exploratory study found stage-related variation in team-level SDNN and HF dispersion during CABG procedures. Further work should validate HRV-derived team measures against observed team processes, workload, communication, and surgical outcomes before interpreting them as indicators of team states. With continued validation, team-level HRV dispersion may offer a useful complementary approach for studying dynamic teamwork in safety-critical environments.

This contribution holds several key implications for the Human Factors community. First, physiological monitoring may provide a complementary lens for examining the temporal dynamics of teamwork, supplementing observational and self-report measures. Second, the findings of this work reinforce the importance of interpreting team-level physiological dispersion in light of individual- and team-level factors, given the heterogeneous roles and demands in complex teams. Third, while this work represents an early attempt to aggregate individual physiological data to reflect team-level phenomena, it illustrates the potential for such approaches to contribute to theory development by enabling the exploration of how team states across time and contexts can offer an empirical insight into an area that has historically been constrained by static research designs (Coultas et al., 2014; Fyhn et al., 2023).

This line of research aligns with the vision articulated a decade ago: developing innovative, data-driven approaches that can add to our understanding of, and ultimately improve, team performance.

Impact statement

Team-level HRV dispersion offers a potential way to study how physiological variability within surgical teams changes across different stages of an operation. The present exploratory study found stage-related variation in SDNN and log-transformed HF dispersion, with HF differences particularly evident during closure relative to selected earlier stages. Further validation against observed team processes may help establish the measure's practical relevance and inform future research and training approaches to surgical teamwork.

Statement for studies in humans/animals

Archival data from an Institutional Review Board (IRB)-approved research project were used in this study (Approval No. 3296; granted on July 7, 2020). All study procedures complied with relevant ethical standards. Informed consent was obtained from all participants prior to data collection, and participant confidentiality was protected throughout the study.

CRediT authorship contribution statement

Maha Khalid: Writing – review & editing, Writing – original draft, Formal analysis, Conceptualization. **Vaibhav Unhelkar:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Marco A. Zenati:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization. **Eduardo Salas:** Writing – review & editing, Writing – original draft, Supervision, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Vaibhav Unhelkar reports financial support was provided by National Science Foundation. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.hfh.2026.100163.

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