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Does heart rate variability predict and improve performance in pediatric CPR?—a simulation study

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Abstract

Introduction Out-of-hospital pediatric resuscitation is a severe medical condition with a low survival rate. Providing pediatric resuscitation is a significant stressor for medical teams that may impair performance. The vagal nerve is a crucial moderator of stress responses, and its activation (indexed by heart rate variability, HRV) has been shown to predict and improve performance in various settings. However, there is limited data about vagal activation and performance in medical settings.

Methods In a randomized simulation Study, paramedic students and medics were assigned to 3 min of slow-paced breathing or watching an educational 3-minute video. The participant received a scenario describing an unconscious baby without a pulse and with no breathing. The participants then performed CPR (cardiopulmonary resuscitation) on a manikin. During the scenario, every 2 min, the participant was asked a question that tested the recall of information from the scenario, and CPR performance was continuously monitored. HRV and subjective stress were taken 3 times.

Results Higher baseline HRV predicted better CPR performance. No difference in CPR performance between the groups was found, and explanations for these results will be discussed.

Conclusion HRV may be used to predict CPR performance. Short-term slow-paced breathing does not improve CPR performance. Future studies should investigate the effect of long-term stress reduction interventions on CPR performance.

Keywords Pediatric CPR, Performance, Vagal activation, HRV

Introduction

Pediatric out-of-hospital cardiac arrest (OHCA) is characterized by low survival rates and poor neurological outcomes [1, 2]. Children's emergency care is a significant stressor for medical teams [3, 4]. Evidence of the negative impact of stress on performance in these contexts is well documented [5, 6]. The cognitive appraisal theory [7, 8] suggests that the individual stress response depends on his or her threat appraisal. Physiological stress responses begin when individuals perceive the situation as a threat (lack of sufficient resources) [9]. In the emergency medical context, stress responses were observed only in

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caregivers who perceived the situation (CPR) as a threat [10]. Thus, finding ways to reduce stress appraisal, reduce stress responses, and improve performance is pivotal.

When a stimulus is classified as a threat, the sympathetic system begins a rapid response (within seconds) of releasing catecholamines (neurotransmitters), which causes (among other things) an increase in heart rate (HR) and breathing rates [9]. Alongside the activation of the sympathetic nervous system, there is an activation of the hypothalamus-pituitary-adrenal axis (hereafter HPA) [9, 11]. HPA activation leads to the release of cortisol, impacting brain regions involved in cognitive processes, such as the frontal cortex, the hippocampus, and the amygdala [9, 12].

The vagus nerve is the main part of the parasympathetic branch of the autonomic nervous system [13]. The vagus moderates the intensity and duration of stress responses (e.g., blood pressure) [14] but not in all situations [15]. Heart rate variability (HRV) represents changes in the intervals between normal heartbeats and can be used to index vagal nerve activity [16, 17]. The vagus nerve can be activated by slow-paced breathing (SPB), which increases HRV [18]. The mechanisms linking paced breathing to vagal activity are complex and include triggering baroreceptors and respiratory sinus arrhythmia [19, 20]. SBP, with a phase of long exhalation, is a commonly used technique to increase vagal activity, which occurs mainly during exhalation [21]. SBP has been found to decrease stress responses and improve performance in nonclinical populations [22, 23].

According to the neuro-visceral model, the frontal brain regulates the autonomic nervous system's activity to provide an adaptive response to environmental demands [24, 25]. This model assumes that the positive relationship between HRV and performance will be preserved even during stressful situations [25, 26], and this is supported empirically [27, 28]. High resting HRV levels are assumed to predict better performance in such conditions since they correlated with cognitive flexibility and inhibition, which are crucial for performance under stress [29]. Taken together, recent systematic reviews indicated that HRV could be used to measure acute stress responses, and that vagal nerve activity could be used as a target for performance improvement in emergency settings [30, 31]. Although the samples mentioned weren't medical teams (primarily in a military context), they linked higher HRV to better cognitive function, reaction time, and sound recalls, all relevant to perform in an emergency medical setting.

When interpreting HRV data, the time point and context in which the measurement is performed must be considered the expected physiological response. For example, high HRV is considered adaptive during rest in most cases [32]. Conversely, as a response to physiological stress, a lower HRV is expected due to the increase in the body's metabolic activity and sympathetic response, which will provide an adapted response to the situation [33]. However, when the individual faces a stressor that requires the activation of executive functions, a decrease in vagal activity may impair the ability to respond appropriately to the threat [25, 34]. It is important to note that high HRV is influenced by many possible sources and generally indicates the ability of the system to adapt to changing environmental demands [24].

High-quality CPR is essential for patients' survival and favorable neurologic outcomes [35]. Repeatedly, emergency teams have reported high-stress levels with a lack of sufficient skills for caring for children [36, 37]. These may contribute to performance deficiencies in prehospital pediatric CPR [38, 39]. Despite the evidence of these stress levels, there is a gap in knowledge and contradictory findings about the impact of stress on performance in this setting. This gap raises the need to identify accurate CPR performance predictors and develop evidence-based, accessible, and brief stress-reduction interventions.

The first purpose of the current study was to examine the ability of resting HRV to predict stress responses and CPR performance. Second, we investigated SPB's effects of short vagal activation on performance during simulated CPR.

Hypotheses

1. Resting HRV levels would be positively related to CPR performance as well as verbal fluency while being negatively related to stress levels.
2. In the second part of the study, we randomized participants to SPB or control groups. The SPB group will demonstrate lower stress and threat appraisal levels and better CPR performance than controls. Executive functioning (as measured by verbal fluency) mediated the intervention group's effect on stress and performance.

Methods and materials

Participants and Procedure: Between January 2023 and May 2023, we recruited 57 participants, paramedic students from two academic institutions (Ben Gurion University and Zefat Academic College) and pre-hospital medics.

All participants were at least at the EMT (emergency medical technician- had received approx. 200 h of training with basic pediatric life support training) level of training. Participation was voluntary, and the participants received a modest gift (bought from our laboratory budget) after their participation.

Based on the study of Le Blanc et al. [40] and assuming a 30% improvement in the intervention group (based on the study of De Couck et al. [41] assuming a statistical significance of $p < 0.05$ and a statistical power of 0.80, the desired sample size was 56 (28 participants in each group).

Study design

We performed an experimental study where half of the participants were randomly assigned (an online randomizer was used at www.random.org) to perform SPB before simulated CPR. After providing consent, participants received an e-mail with instructions to refrain from smoking and drinking coffee two hours before the study, as recommended for studies that measure HRV [32]. On the study day, each participant filled in an online form with personal details and informed consent and was asked to rest for 5 min to establish a "baseline" before the measurement was obtained. Then, a 2-minute HRV measurement was taken while the participant was seated upright. Thereafter, stress and verbal fluency were measured. Subsequently, the intervention group practiced 3 min of SPB (inhale for 4 s, hold breathing for 1 s, and exhale for 5 s) using the EZ software as a breathing pacer [21, 42]. The control group watched an educational 3-minute video on the immune system. At the end of the video or the breathing task, each participant received a scenario describing an unconscious baby without a pulse and with no breathing. The participant was then asked two threat and challenge appraisal questions (full description is provided in the method section) and then was asked to perform CPR (at BLS level) on a manikin. Following AHA recommendations [43], a metronome (110 beats per minute, available in many monitors or defibrillators in the prehospital and hospital setting) was activated when the participant began CPR. During the scenario, in 1-minute intervals, the participant was asked a recall information question (see below), and CPR performance was continuously monitored. After five minutes, the scenario ended, measurements were retaken, and after 10 min of rest, measurements were taken for a third time. For the full study protocol, see Fig. 1. All data were collected between 1.2023 and 5.2023.

The study has been approved by institutional IRB protocol number 508/21.

Background questionnaire: was built for the study. The personal information included age, gender, academic year, level of EMS training, and years of experience.

Medical background: Arrhythmia, antiarrhythmic drugs.

Physiological measures

Throughout the scenario, we collected three segments of 2-minute HRV s [44]. HRV was measured with the eMwave pro (https://www.heartmath.com), which has been used in many studies and enables to measure time domains [45, 46]. The eMwave pro measures by photoplethysmography optical detection of a change in blood volume on the skin's surface with a sampling rate of 370 **Hz**, representing heartbeats. The time interval between the waves was used to calculate HRV [47]. We obtained time domain measures that were found to be less affected by breathing [48]. For HRV measurement, see supplemental data 2.

SDNN (Standard deviation of normal-to-normal intervals): This index is calculated as follows: First, all distances between two consecutive normal beats are calculated in

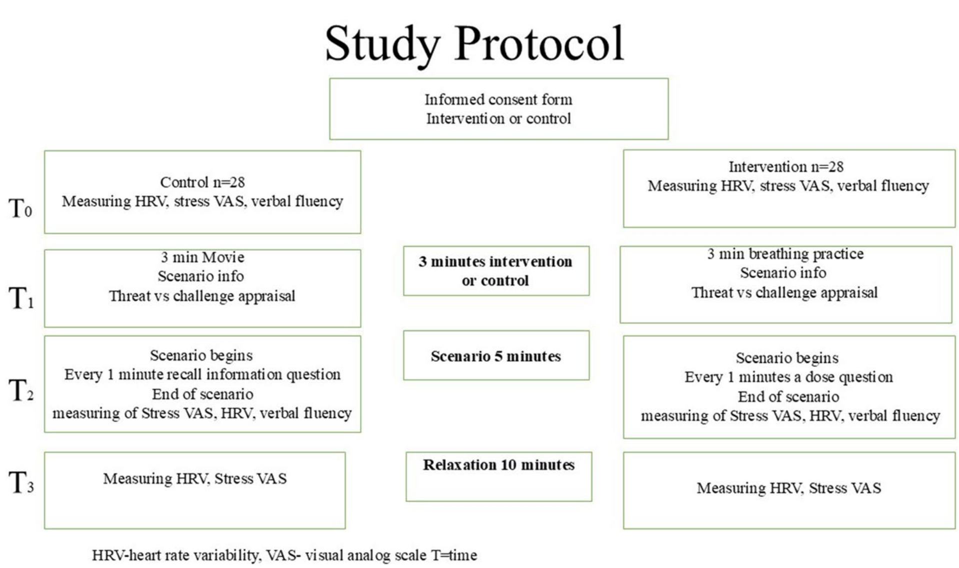

Fig. 1 Study protocol

milliseconds, and the mean of the results is calculated. Then, the deviation of each interval from the mean is calculated, and finally, the mean of the deviations is calculated (All values are provided in Milliseconds). SDNN is affected by all factors contributing to HRV (sympathetic and mostly parasympathetic) [20].

RMSSD (Root mean square of successive differences between normal heartbeats): The index is calculated as follows: First, all distances between two consecutive normal beats are calculated in milliseconds. Secondly, each of the received values is squared, and the result is average. Finally, the root mean of the squares is calculated (all values are provided in Milliseconds). The index assesses vagal activity and is less affected by breathing [20].

The SDNN and RMSSD values provided in the results section are mean values with the standard deviation, and the values are in milliseconds.

Psychological measures

Cognitive appraisals Based on Harvey et al.'s research [10], The cognitive appraisal included two questions asked one after the other, after the participants were given the scenario and before he began the CPR. The primary appraisal was assessed by asking the participants, "How stressful do you expect the upcoming task to be?" before the scenario. Then, secondary appraisal was measured by asking the participants, "To what extent do you have the resources to handle the task?"

Participants rated their answers on a 10-point Likert scale. An index of cognitive appraisal was then calculated as the ratio of the primary appraisal (demands) to the secondary appraisal (resources). If the resources were assessed as equal to or greater than the task demands, the situation was appraised as a 'challenge' (ratio ≤ 1). If the task demands were more significant than the resources, the situation was appraised as a 'threat' (ratio > 1).

Veencyrbal fluency The verbal fluency test [49] is in widely used for evaluating executive function performance. Participants were given 1 min to produce as many unique words as possible, starting with a given letter (phonemic fluency). The participant's score in each task was the number of unique correct words. The test was administered twice, in the baseline measure (T0) and right after the experiment (T2), using different first letters, and the order of the words was randomized between participants.

Stress levels Each participant was asked to rate his perceived stress level on a scale of 1–10, similar to a VAS scale. VAS scales are commonly used in stress studies and are highly correlated with reliable stress assessment tools [50].

Performance measures

Performance in CPR The performance was analyzed using a Laerdal Medicapediatric manikin (Laerdal Medical AS, Stavanger, Norway). The sensor provides feedback on various CPR parameters [51]. In this study, the depth and number of chest compressions were analyzed according to American Heart Association (AHA) recommendations [52].

Chest compression rate: The AHA recommended massage rate for babies is between 100 and 120 compressions per minute [52] To calculate this variable, we created a dichotomous variable. Participants who performed between 100 and 120 massages per minute were classified as correct performers (2), and those who performed above or below this range were classified as incorrect (1).

Chest compression depth According to AHA guidelines for infants and children, chest compressions should depress the chest by at least one-third of the anterior-posterior diameter [52]. For our study, the correct compression depth range for the manikin is 38–50 mm (Laerdal in-person communication). Participants who performed within this range were classified as correct performers (2). Participants who performed above or below this range were classified as incorrect (1).

Information recall In line with Leblanc and others [53], we built a seven-item questionnaire that tested memory for information required for patient care. The questionnaire included questions about the patient's background (e.g., allergies) and current condition (e.g., fever). For each correct answer, the participant got 1 point.

Data and statistical analysis We provide descriptive and inferential statistics. We used mean values only for HRV measures. For HRV analysis, we used Kubios software (https://www.kubios.com), which allows analysis of the time and frequency of HRV domains and has been used in many studies. We used the default recommendations for data screening and cleaning [45, 46]. We examined correlations between baseline HRV and recall information scores, VAS stress, and Verbal fluency using Pearson correlations. Verbal fluency was measured twice (T0, T2). Vas stress and HRV were measured three times (T0, T2-3), and this was taken into account in the repeated measure ANOVA). We use two main analyses to answer our research questions. First, we used t-tests to compare groups on the continuous outcomes measured only once - memory and CPR performance scores. Second, we performed a mixed-design analysis of variance (ANOVA) on continuous outcomes measured several times where we focused on the Time (T0, T2 or T0, T2, T3, depending

Table 1 Differences between groups in baseline measures

Variable	Intervention group ($n=26$)	Control group ($n=24$)	Differences
RMSSD (milliseconds)	M = 52.51 ± 24.09	M = 47.48 ± 18.73	t (48) = 0.819, p = 0.0.417
SDNN (milliseconds)	M = 50.43 ± 22.70	M = 48.4 ± 21.65	t (48) = 0.324, p = 0.0.748
LOG RMSSD	M = 1.68 ± 0.18	M = 1.64 ± 0.15	t (48) = 0.684, p = 0.0.497
LOG SDNN	M = 1.66 ± 0.19	M = 1.64 ± 0.18	t (48) = 0.288, p = 0.0.774
VAS stress	M = 1.82 ± 1.16) $N=29$	M = 2.29 (± 1.68) $N=27$	t (54) = -1.21, p = 0.0.228
Verbal fluency	M = 11.10 ± 5.95 $N=29$	M = 11.75 ± 4.38 $N=28$	t (55) = -0.465, p = 0.0.643

RMSSD = Root means square of successive differences between normal heartbeats. SDNN = Standard deviation of normal-to-normal intervals. M = mean

Table 2 Pearson correlations between heart rate variability (HRV) recall information scores and stress levels

HRV	Recall information test	Verbal fluency T2	VAS stress T2
RMSSD (milliseconds)	0.127	-0.051	-0.08
SDNN (milliseconds)	0.214	-0.026	-0.077
LOG RMSSD	0.169	-0.104	-0.049
LOG SDNN	*0.257	-0.09	-0.037

*$P < 0.05$

RMSSD = Root means square of successive differences between normal heartbeats. SDNN = Standard deviation of normal-to-normal intervals

Immediately after the end of the CPR simulation

on the variable) by group (experimental, control) interaction in relation to HRV and perceived stress. Statistical analyses were conducted using IBM SPSS Statistics 27.0 software. Based on the study by LeBlanc et al. [51] and assuming a 30% improvement in the intervention group [38], setting a statistical significance of $p < 0.05$ and a statistical power of 0.80, the desired sample size was 56 participants (28 participants in the group).

Results

Descriptive statistics

Approximately 120 participants were invited, and the study included 57 participants (mean age 29.31± 10.29) who responded to our invention. There was no difference in the background variables between the groups (all $p > 0.05$) (see supplemental data 1). Additionally, no difference was found in the baseline measures for RMSSD, SDDN VAS stress, and verbal Fluency, as seen in Table 1. Thus, randomization was successful. Unfortunately, some data regarding CPR performance quality (13 cases) was lost for reasons beyond our control. In addition, after analyzing heart rate variability indices, some of the measurements with poor quality were not included, which is the reason for the change in the number of participants in some analyses.

Relation between heart rate variability (HRV) recall information scores and stress levels

To test the first hypothesis, we calculated Pearson correlations between VAS stress, verbal fluency, and information recall score with RMSSD and SDNN (separately) variables after controlling for the effects of the group (intervention or control). As in many other studies, the HRV data were not normally distributed. Hence, a log transformation was applied as recommended for the analyses [32]. For comprehensibility, the log-transformed data were used in the inferential statistical analyses, while the non-log-transformed original data were presented in the descriptive statistics. As seen in Table 2, we found a significant positive weak correlation only between log-SDNN and recall memory score, $r = 0.28$ $p = 0.04$.

For CPR performance, a t-test for independent samples was performed. Participants who performed in the recommended compression rate ($n = 31$) had higher baseline RMSSD (49.7±22.83) and SDNN (50.93±22.78) than those without adequate compression rate ($n = 8$) RMSSD (38.13±7.20) and SDNN (34.75±6.49). However, only the SDNN was significantly higher (t (37) =-1.72,p = 0.0.012). For compression depth, the participant who performed in the adequate depth ($n = 28$) had higher baseline RMSSD (48.89±21.69) and SDNN (48.13, 20.9) compared to participant who performed inadequately ($n = 11$), RMSSD (43.32,±19.76) and SDNN (44.75±23.54). Both differences were not significant ($P > 0.05$). These results aren't changed after controlling for past EMT experience (data not shown).

Effects of the intervention on study outcomes

To examine the second hypothesis, we performed t-tests for independent samples. No difference was found between the groups on information recall score (t(55) = 0.23, $p = 0.62$; Cohen's d = 0.06). We also calculated the chi-square for cognitive appraisal and chest compression rate and depth, as well as scores as categorical outcomes, and again, no differences were found between groups (see Table 3). In relation to verbal fluency, there was no difference between the two measures in the intervention group (11.1 + 5.9;12.34 + *5.2)* or the

Table 3 Differences between groups in performance measures and cognitive appraisal

Variable		Intervention group $n=29$	Control group $n=28$	Differences
Recall information score		M = 5.03 ± 1.11	M = 4.96 ± 1.13	t (55) = 0.235, p = 0. 815 Cohen's d = 0.062
Compression rate (no. of cases)	Correct	18	17	χ^2 (1) = 0.140 p = 0.709
	Un correct	4	5	
Compression Depth (no. of cases)	Correct	8	17	χ^2 (1) = 0.983 p = 0.322
	Un correct	14	5	
Cognitive appraisals (no. of cases)	Threat	13	9	χ^2 (1) = 0.596 p = 0.44
	Challenge	16	17	-

M = mean S.D = standards deviation

control group (11.75 ± 4.38;12.92 ± 4.89*)*. The time by Group interaction was not significant (F(1,55) = 0.003, p = 0.95).

The Time by Group interaction was insignificant in relation to perceived stress (F(2,100) = 1.18 P = 0.311). It was also insignificant concerning RMSSD (F(2,72) = 0.3 P = 0.737). Finally, it was insignificant in relation to SDNN (F(2,72) = 1.71 P = 0.19). However, the pattern of results tended to show an apparent increase in SDNN only in the experimental group. Since there were no effects for groups on verbal fluency and performance, we didn't test the mediating role of verbal fluency.

Discussion

The study's first aim was to examine the ability of HRV to predict aspects of CPR performance and stress responses. The second aim was to examine the effects of short SPB on stress responses and CPR performance. As expected in the first hypothesis, baseline HRV (SDNN) was positively correlated with performance in a recall test and with adequate chest compressions according to AHA guidelines. These abilities are essential for providing high-quality CPR. These results are in line with a recent systematic review indicating that HRV can be used to predict performance in operational work environments and EMS (Emergency medical services) organizations [31]. Unlike that review, we found no significant correlation between HRV and subjective stress. One explanation is that most participants didn't find the simulation as stressful. In addition, since the study was done in an academic setting, students may have been reluctant to report high stress levels due to fear of being judged.

Our hypothesis wasn't confirmed regarding verbal fluency. As seen in the background table (supplemental data 1), Hebrew wasn't the first language of 19 of the participants, and this might have influenced the results of the verbal fluency test.

The second hypothesis was not confirmed. Groups didn't differ in their CPR or recall information performance, and there could be several explanations for this. Regarding the quality index of CPR (message depth and rate), it is possible that short breathing training may not be sufficient to influence it since it is a motoric index of performance. This explanation is supported by a recent meta-analysis that found no relationship between slow breathing practice in short-term interventions and sports performance [54]. Longer breathing interventions may have stronger effects on performance. Furthermore, since SPB may influence certain sections of performance at the creation time point (e.g., first shooting) [55], future studies should examine this further in detail". Although the intervention group demonstrated better performance in the memory score, it was not statistically significant. Since all the participants demonstrated relatively high performance, the null effect of the group may have resulted from this ceiling effect, making the memory test and performance measures less sensitive.

Grubish et al. [55] found that following tactical breathing, a higher proportion of successful intubation was found for ER residents compared to controls (100% success vs. 85% respectively). However, tactical breathing didn't influence intubation time, their study included physicians, while our study included paramedic students. To the best of our knowledge, no other studies on the effects of slow breathing were conducted in an acute healthcare setting. In the military context [56], 160 s of tactical breathing was found to improve marksmanship performance only in the first out of 10 shots.

In laboratory studies, SPB was found to improve abilities essential to performing under stress, such as decision-making, error monitoring, and inhibition [23, 41, 57].

These contrasting results could be due to different durations of SPB or differences in the task itself and the setting (laboratory vs. simulator).

Relating to the effect of slow-paced breathing on emotional responses, a recent meta- analysis [58] found a marginal effect of SBP on subjective outcomes. However, the duration of breathing was longer than 5 min and not in the emergency context. Since EMS is a high-stress setting [59–62] and given the possible positive impact of breathing on stress and performance, more research is needed.

Our study had several limitations. First, as a simulator study, caution is needed in drawing conclusions about real-life CPR [6]. In real-life conditions, it is plausible that other factors (e.g., family members' presence) may serve as noise variables that are not present in simulated conditions. We assume that stress levels would be higher in a real-life situation, and SPB may have positively affected CPR performance. Second, due to data loss and technical issues, the number of participants was smaller than desired for some outcome measures. Furthermore, our sample was not randomly selected. These limitations reduced our generalizability and statistical power. Additionally, other more sensitive performance measures are needed due to ceiling effects. Lastly, our sample included 19 participants for whom Hebrew was not their first language. Since their studies are in Hebrew, it was not expected to influence their CPR performance, but it might influence their verbal fluency, and this needs to be considered in future studies.

Nevertheless, our study showed that resting HRV may be used to predict performance in CPR. Since OHCA's survival rate is very low [1–3], finding ways to improve it is critical. Since HRV may be used to predict performance, health systems and EMS organizations may develop AI tools that combine HRV and other predictors monitoring with routinely high-quality training [63]. Additionally, health professionals with low HRV could benefit from increasing their HRV by biofeedback or by having more training to improve their performance. In future studies, it is recommended to test the effect of long-term stress reduction interventions on the emergency teams' CPR performance.

Abbreviations

AHA	American heart association
CPR	Cardiopulmonary resuscitation
EMS	Emergency medical services
HRV	Heart rate variability
OHCA	Out-of-hospital pediatric resuscitation
RMSSD	Root mean square of successive RR interval differences
SDNN	Standard deviation of NN intervals
SPB	Slow-paced breathing

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s12873-025-01209-9.

Supplementary Material 1

Supplementary Material 2

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Author contributions
YK: Conceptualization, Formal analysis, Investigation, Writing – original draft. OW: Conceptualization, Writing – original draft, supervision. IBS: Conceptualization, Writing – review & editing. AG: Formal analysis. YG: Conceptualization, Formal analysis, Writing – original draft, supervision.

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Data availability
The datasets used and/or analyzed during the current study are available from the corresponding author upon reasonable request.

Declarations

Ethics approval and consent to participate
The study has been approved by Haifa University IRB protocol number 508/21.

Consent for publication
Not applicable.

Consent to participate
All participants in this study have voluntarily expressed their consent to participate.

Competing interests
The authors declare no competing interests.

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