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Detecting effects of yoga therapy on heart rate variability and autonomic nervous system functioning in adults after cancer treatment: results from a study using single-subject experimental methods

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Abstract

Background Cancer is a source of physiological and psychological stress. Heart rate variability (HRV) is a measure of autonomic reactivity to physiological and psychological stress. For an initial proof-of-concept, we investigated the effects of a yoga therapy (YT) intervention on HRV metrics and self-reported autonomic nervous system (ANS) functioning using single-subject experimental methods.

Methods Data from 20 adults ($M_{age\ (years)} = 55.7$ [$SD = 8.6$], 85% female, $M_{years\ from\ diagnosis} = 2.8$ [$SD = 3.5$]) were analyzed. Participants received an initial 90-min 1:1 YT session followed by 6 weekly 60-min small group YT sessions. Hexoskin Smart Shirts captured single lead electrocardiographic data suitable for HRV analysis, and questionnaires were used to assess self-reported state and trait ANS functioning. Data collected *prior to* (weeks − 6, −3, and 0a), *during* (immediately after the 1:1 YT session [week 0b] and before the first group session [week 1]), and *after* (weeks 7 and 12) the YT intervention were analyzed. Hierarchical linear modeling (HLM) was used to estimate average baseline levels (*intercept*), linear slopes (*time*), YT initiation effect on levels (*phase*), and YT intervention effect on linear slopes (*time-by-phase*) for each outcome.

Results HLM yielded mixed results. Significant ($p < 0.05$) *time*, *phase*, and *time-by-phase* effects for state ANS, coefficient of variation and high frequency power, *time-by-phase* effect for trait ANS, and *time* and *phase* effects for sample entropy were observed. No significant effects were observed for remaining analyzed HRV metrics.

Conclusions Though mixed, results establish an initial proof-of-concept required to justify larger studies investigating the effects of YT on HRV and self-reported ANS functioning in adults after cancer treatment.

Trial registration name ISRCTN registry.

Registration number ISRCTN64763228.

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URL of trial registry record https://www.isrctn.com/ISRCTN64763228.
Keywords Autonomic function, Heart rate variability, Yoga, Neoplasm, Integrative oncology

Introduction

Persons diagnosed with cancer who have undergone curative-intent treatment experience physical (e.g., physiological effects of surgery and treatment) and psychological (e.g., perceived threats, fear, worries, intrusive thoughts) stimuli that can disrupt homeostasis and trigger a stress response [1, 2]. The acute stress response that typically results from immediate stimuli can cause physiological reactions including increased heart rate, elevated blood pressure, altered breathing patterns (e.g., shortness of breath, rapid shallow breathing), and musculoskeletal tension [3]. Whilst these reactions to acute stress are important for self-preservation, they become maladaptive in the face of chronic stress (i.e., stress that occurs when the stimuli persist over an extended period) [3]. Chronic stress can exert cumulative, detrimental effects on both physiological and psychological health. Consequently, it can increase the risk of health problems such as depression, anxiety, fatigue, cognitive impairment, and heart disease, disrupt sleep patterns, and impair daily functioning [3, 4]. Additionally, acute and chronic stress can disrupt autonomic nervous system (ANS) functioning [5, 6], which controls involuntary body functions such as breathing, blood pressure, heartbeat, and the dilation (or constriction) of blood vessels and small airways in the lungs [7]. Disrupted ANS functioning can compromise immune function and increase the risk of morbidity and early mortality [4]. Collectively, stress responses can prolong recovery and worsen quality of life.

Measuring stress response

Various techniques are used to assess people's stress responses or autonomic reactivity. The use of self-report questionnaires is common because they are inexpensive, easy to administer in large scale studies, and can contribute information about people's perceptions of their psychophysiological reactivity in their ANS to stress-provoking stimuli. However, people's perception of their autonomic reactivity is not always related to their physiological experiences. Thus, in addition to self-report questionnaires, it is important to include objective autonomic measures when investigating the effects of interventions on people's stress responses.

Analysis of heart rate variability (HRV) is commonly utilized to measure ANS cardiac modulation. HRV analysis measures the patterns of variation in the time interval between consecutive heartbeats, reflecting the balance between the two different nervous systems. The first, the parasympathetic nervous system (also known as the "rest and digest" system), is emphasized when the body is relaxed and at ease, thinking is clear, heart rate is relatively slow, and breathing is deep and full. The second, the sympathetic nervous system (also known as the "fight-or-flight" system), is mobilized during a perceived threat to enable a person to either fight the threat or flee the situation [8]. During a stress response, the body undergoes changes in the ANS, including vagal withdrawal (reducing parasympathetic activity) and sympathetic activation (increasing sympathetic activity); as this leads to an increase in heart rate [6], HRV is widely used as a non-invasive, non-specific marker of ANS functioning [6, 9, 10]. Several variables within three domains contribute to HRV assessment: *time* (i.e., quantify the variation in time intervals between successive normal cardiac cycles), *frequency* (i.e., quantify the contribution of the parasympathetic nervous system and the sympathetic nervous system), and *complexity* (i.e., quantify the unpredictability and complexity of changes in inter-beat intervals) [11].

Increased (or higher) HRV reflects longer, less rhythmic intervals between heartbeats and is associated with stress resilience and well-regulated ANS functioning (i.e., a healthy response of the parasympathetic system). Indeed, such patterns are believed to reflect a greater physiological capacity for emotional regulation in response to stress [12]. Conversely, decreased (or lower) HRV reflects shorter, more consistent periods between heartbeats, which typically occur when the heart beats faster. This is associated with impaired regulatory and homeostatic ANS cardiac modulation and function (e.g., sympathetic dominance, vagal withdrawal), which reduces the body's ability to cope with stressors. Decreased HRV has significant implications. For instance, it can promote the development of atherosclerosis, compromise vascular function, suppress immune function, and exacerbate cardiovascular risk and respiratory symptoms [13]. Decreased HRV is also associated with psychological health problems (e.g., depression, anxiety) and reduced quality of life [14–16]. In persons diagnosed with cancer, decreased HRV has been observed based on linear (i.e., time and frequency domains) and nonlinear (i.e., complexity) metrics [17–20]. For example, compared to matched controls, women diagnosed with breast cancer have shown significantly faster heart rates and lower HRV as indicated by lower values for standard deviation of normal-to-normal intervals (SDNN), square root of

mean squared differences of successive normal-to-normal intervals (RMSSD), HRV index, and high-frequency (HF) power [20]. This could be, in part, attributed to the high occurrence of stressful stimuli and suggests that interventions that help reduce the autonomic reactivity to stress are warranted.

Yoga interventions

Whilst numerous yoga styles exist worldwide (e.g., Hatha, Iyengar, Vinyasa, Ashtanga, Sivananda, Restorative), each reflecting a cultural heritage and/or post-lineage practice, most share the intention to unite the mind, body, and spirit through varied practices [21]. Popular styles integrate *asana* (i.e., physical postures sometimes woven together in a series called *vinyasas*), *pranayama* (i.e., conscious observation, control, expansion, retention, and manipulation of the breath), and *dhyana* (i.e., meditation) practices along with yogic philosophy that emphasize practicing self-compassion and attending to obstacles that underlie human suffering (i.e., *kleshas*) [21]. Importantly, dedicated yoga practice is not just about fitness (e.g., increasing stamina, balance, flexibility, and muscle strength); it is also about cultivating self-awareness and helping people discover how their thoughts and beliefs can affect how they feel and experience life in their bodies (and vice versa) via practices to withdraw the senses (i.e., *pratyahara*), concentrate the mind (i.e., *dharana*), and develop unwavering awareness (i.e., *dhyana*) [21]. These days, many people in Western countries practice yoga to promote subjective perceptions of relaxation, free their mind from worries, optimize their psychophysiological responses to stressful stimuli, and make positive physical, mental, and spiritual changes [21]. This has piqued the interest of researchers and stimulated research on the effects of yoga on numerous outcomes.

Comprehensive reviews of studies with persons diagnosed with cancer practicing different yoga styles, with varying duration and frequency (i.e., dosage), have shown positive effects on perceived stress and stress-related outcomes, including distress, depression, anxiety, fatigue, emotional functioning, social functioning, functional wellbeing, and quality of life [22–29]. There is also evidence that different yoga styles have positive effects on respiratory, cardiovascular, and ANS functioning in people with and without a cancer diagnosis [30–34]. For example, documented effects of yoga on the ANS include increased vagal activity (vagal tone), a shift toward parasympathetic dominance, and enhanced phasic modulation of sympathetic activity [33, 35–37]. Still, analysis of HRV in studies investigating the effects of different yoga styles with persons diagnosed with cancer is scarce, making it crucial to study specific, well-defined interventions to understand their unique effects. Herein, we used a novel approach to analyze HRV among persons who participated in yoga therapy (YT) after cancer treatment. Specifically, we analyzed data derived from recordings produced by smart garments equipped with wearable sensors that provide continuous cardiac and respiratory monitoring to analyze HRV metrics prior to, during, and following YT. We also analyzed self-reports of ANS functioning to assess *perceived* autonomic function in daily life.

Another novelty of this study is the delivery of *YT*—a personalized, non-prescriptive, progressive, and integrative yoga style—to affect HRV and ANS functioning; this differs from previous studies focused on the wider practice of yoga featuring standardized sets of poses and breathing exercises often performed in medium-to-large group settings. YT is defined as "the process of empowering individuals to progress toward improved health and wellbeing through the application of the teachings and practices of yoga" [38]. Whilst both YT and yoga can be therapeutic, take place one-to-one (1:1) or in group settings, share techniques, and have similar overarching intentions, YT is unique and distinct from the wider practice of yoga. One key difference is that people seek YT to get help with or relief from specific symptoms or health conditions (e.g., pain management, cancer-related fatigue, fear of cancer recurrence), and will thus take part in a detailed assessment. In turn, yoga therapists focus on the whole person (i.e., the many layers of being or the koshas). They will attend to specific symptoms or health conditions that affect the person (in the case of 1:1 sessions) or people (in the case of *small* group sessions), and identify relevant yogic philosophy, lifestyles, and practices that will promote self-awareness, self-management of symptoms or conditions, and nourish physical, mental, and spiritual wellbeing. Another key difference is that yoga therapists have substantially more training than yoga teachers/instructors to: (1) gain knowledge of medical diagnoses, various health conditions, medical treatments and associated effects, and contraindications, (2) build psychotherapeutic skills and a deep understanding of the therapeutic relationship, (3) gain knowledge of yoga practices to prescribe based on people's needs and health status, and (4) recognize professional boundaries and understand other health professionals' roles (for referral purposes). Although the terms *yoga* and *YT* have been used interchangeably, likely because different yoga styles can have "therapeutic" effects, the complex, holistic approach of YT has seldom been examined in oncology settings. As people managing the impacts of cancer treatment may turn to YT to address specific health conditions, manage symptoms, and improve function in a therapeutic context, we sought to build further credibility for its future implementation and evaluation in research and supportive care settings.

Current study

In a single-subject experimental study, we aimed to test the effects of a YT intervention delivered at the Centre for Health Innovation (CHI) on repeated HRV metrics (primary outcomes) and self-reported secondary outcomes related to ANS functioning, physical symptoms, psychosocial problems, cognitive function, and quality of life in persons who had completed cancer treatment. The specific objective of the present study was to test the effects of the intervention on HRV metrics and self-reported ANS functioning; results for remaining outcomes are presented elsewhere [39]. Drawing on relevant literature that the wider practice of yoga promotes favourable physiological adaptations, we hypothesized that the YT intervention would positively affect HRV metrics and self-reported ANS functioning over the course of the study. Support for our hypothesis would then justify moving forward with additional research to test the efficacy of YT in larger confirmatory studies.

Methods

Study design, setting, and procedures

This was a single-subject, unblinded experimental study, which is ideally suited for this early-phase and exploratory research designed to secure an early signal of treatment effect (rather than confirm efficacy) [40]. The goal was to determine if this line of research is promising enough to pursue more comprehensive and resource-intensive studies, ultimately guiding an informed "go/no-go" decision. The 2025 Consolidated Standards Of Reporting Trials (CONSORT) checklist [41] was used while preparing this manuscript as a tool to enhance reporting; however, there was not complete adhesion to all CONSORT items given the characteristics of this study (e.g., randomization items were not contemplated; see Additional file 1 for completed checklist). The full protocol is described in detail elsewhere [42]. Methods and results that are not the focus of this study are omitted from this manuscript. The study took place at the CHI in Ottawa (Ontario, Canada). Figure 1 illustrates the timeline of the study and when data were collected from participants. Participants were recruited via CHI staff referral and self-referral. Due to the study design, randomization and blinding allocation were not relevant. All enrolled participants completed three assessments prior to commencing the YT intervention (A1 [baseline] phase). Participants then received one 1:1 YT session (i.e., 1 participant, 1 yoga therapist; B1 [intervention] phase) followed by six weekly group-based YT sessions (i.e., 2–3 participants, 1 yoga therapist; B2 [intervention] phase) with two assessments taking place during B1 and B2 intervention phases. The study team recorded attendance to monitor adherence. Finally, participants completed two assessments after the YT intervention ended (A2 [follow-up] phase).

Ethical principles

This study was designed and carried out in accordance with the principles of the Declaration of Helsinki. It was approved by the ethics committees of the University of Ottawa (file no.: #H01-17-04, March 17, 2017) and the Canadian College of Naturopathic Medicine (file no.: CCNMREB016, February 28, 2017). Participation was voluntary, all participants signed an informed consent form, and no financial compensation was provided to participants. During the consent process, participants received study details. These details included a description of the study's purpose, confidentiality and

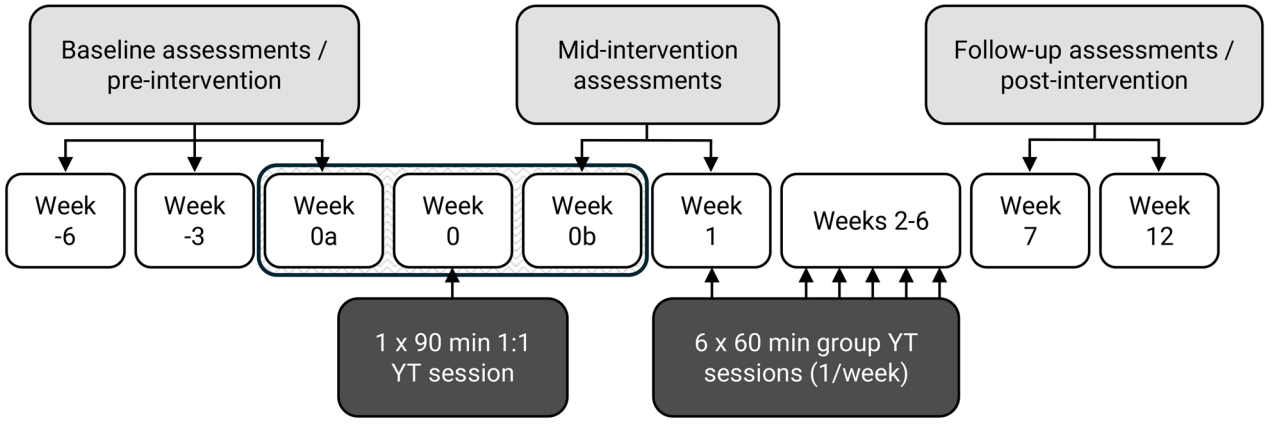

Fig. 1 Timeline of assessments, YT intervention delivery, and follow-up. **Notes**. Light grey boxes with associated white boxes denote assessments. Dark grey boxes denote intervention sessions. Abbreviation: YT = yoga therapy. Week 0: Garments were worn during the 1:1 YT session for heart rate variability (HRV) analysis (analogous to task-related HRV) but were not analyzed given the focus on HRV metrics at rest (analogous to resting state HRV) in this study. It can be argued that any observed effects would be methodological artefact caused by non-equivalent stimuli conditions across conditions (task versus resting). Week 0a and Week 0b reflect HRV data collected immediately prior to and after the 1:1 YT session, respectively. In the week following the 1:1 YT session, participants completed their Week 1 assessments and then began the first of six group YT sessions

data protection strategies, an explanation that participation was voluntary and without obligation, statements that no potential risks or harms (i.e., medical or psychological undesirable events) were expected, details on how study results could be used, and contact information for the primary investigator and institutional review boards. Additionally, the consent form covered the research team's and ethics committees' right to terminate the study (e.g., in instances where procedures were no longer feasible); however, no formal, pre-specified stopping rules were in place. All participants were free to receive care as usual from conventional healthcare and/or allied healthcare professionals in addition to the YT intervention. The study was registered retrospectively in a public registry for clinical trials [43].

Public and patient involvement

No members of the public (including patients) were involved in the design, conduct, and interpretation of this study.

Eligibility

Adults who met the following criteria were eligible: (1) ≥ 18 years of age, (2) diagnosed with cancer, (3) completed curative cancer treatment (i.e., chemotherapy, radiotherapy, surgery) > 3 months prior and not scheduled to receive any for ≥ 5 months, (4) not taking cardiac medication (including beta-blockers), (5) no YT participation since their cancer diagnosis (other yoga styles such as Hatha, Vinyasa, Iyengar, and Ashtanga were allowable), (6) no contraindications to engage in physical activity (as assessed using the revised Physical Activity Readiness Questionnaire; available for download at https://www.csep.ca), (7) agree to provide informed consent, and (8) able to understand and speak English. Because this exploratory study was designed to detect a proof-of-concept across a broad, diverse cohort rather than limiting the scope to a single, homogenous group, these criteria were intentionally broad to yield data more representative of real-world populations. These foundational, signal-seeking results can then inform subsequent, targeted studies focused on specific cancer cohorts.

YT intervention

The YT intervention is described following the CheckList stAndardising the Reporting of Interventions for Yoga (CLARIFY) guidelines [44] in our protocol [42]. Briefly, it was delivered in person at the CHI over a 7-week period and aimed specifically to promote ANS functioning to help relieve stress-induced responses. Delivery involved an initial 90-min 1:1 YT session that included a detailed assessment, followed by six weekly 60-min group sessions. Group sessions were provided to 2–3 participants at a time. Sessions were delivered by one of two yoga teachers who were training with AP to become yoga therapists. Sessions involved check-in/outs, empathetic listening, co-assessment of participants, yogic ANS education, and yoga practices adapted to suit participants' unique physical, mental, and spiritual needs. Yoga practices integrated postures (i.e., *asanas*), mindful somatic movements, breathing exercises (i.e., *pranayama*), meditation, and imagery-based yogic relaxation techniques. Yoga sessions were delivered in English using an established modifiable protocol continually tailored to participants. Participants were encouraged to modify practices themselves, ask for help, rest, and/or consider imagining the practices (rather than completing them physically) if they wished. Soft background music (i.e., "Bija" by Todd Norian) was played during the sessions.

Measures

The 14-item state version [45] and the 19-item trait version [46] of the self-report autonomic regulation (aR) scales were used to assess participants' *general* and *state* status of regulation for different autonomic functions, specifically orthostatic-circulatory, rest/activity, and digestive regulation. State aR items were scored on a 5-point scale, whereas trait aR items were scored on a 3-point scale (both with various anchors across the items). Item 12 of the trait aR scale was removed and negatively worded items on both scales were reversed-scored before summing all items. Score ranges for the state and trait aR scales are 14–70 and 18–54, respectively, with higher scores reflecting better perceived self-regulation of autonomic functions [47].

Hexoskin Smart Shirts (Carré Technologies Inc.; [48]) were worn to record continuous cardiovascular data from the physiological sensors embedded within the garments (i.e., textile electrocardiograph, respiratory inductive plethysmography sensors, tri-axial accelerometer) via Bluetooth. Participants' resting state heart rates were captured via electrocardiograph, and data from these recordings were used to calculate HRV metrics. All participants were familiarized with the assessment procedures during the screening session and asked to refrain from exercise, alcohol, or caffeine for 24 h prior to each assessment. Upon arrival at the CHI, participants were fitted with a Hexoskin Smart Shirt, completed a paper-and-pencil survey, and then sat for 30 min to record heart rate and HRV at rest in a quiet environment. During the recordings, participants were not permitted to read, listen to music through a hand-held device, or use their phone for texting or talking to others; the key was to avoid any activity. Of note, we did not implement a controlled breathing protocol (e.g., paced breathing at a specific frequency and consistent depth) during recordings because we intended to measure participants' natural, spontaneous autonomic function under resting

conditions and the control of breathing may itself affect HRV metrics. Asking participants to consciously control their breathing would have overridden this spontaneous regulation, introducing an artificial, voluntary influence. Rather, participants breathed at their own natural pace and depth. A clear trace was confirmed by a member of the research team prior to the start of participants' recordings. Participants also wore the Hexoskin Smart Shirt during the 1:1 YT session (data during YT not analyzed herein). To minimize circadian influences, attempts were made to schedule participants' assessments at consistent times of day across all timepoints and participants, though flexibility was allowed to accommodate their availability.

To describe the sample, participants self-reported sociodemographic, behavioural, and medical information within the first survey. The following information were collected: date of birth, sex, civil status, cultural and racial background, education level, annual household income ($CAD), employment status, health conditions, height, weight, and cancer-related characteristics (i.e., type, stage, date of diagnosis).

Data extraction

Continuous Individualized Multiorgan Variability Analysis software was used to preprocess the continuous electrocardiograph and respiratory recordings from wearable sensors. Preprocessing included artifact removal (e.g., ectopic beats, missed beats, non-stationarities), noise filtering, and window parsing, with strict criteria applied to ensure data quality prior to further data analysis [49, 50]. Of note, raw data were trimmed to remove the initial acclimation period while preserving long-term variability and maintaining computational feasibility; consequently, only the last 30 min of each session were analyzed. The thoracic and abdominal respiratory signals were linearly combined using weights of 0.71 and 0.29, respectively, and analyses were performed using 10-min moving windows with a 2.5-min overlap [49, 50].

Next, along with mean heart rate, three groups of HRV metrics [51] were generated for analysis: (1) *time* domain (i.e., coefficient of variation [CoV], SDNN, RMSSD); (2) *frequency* domain (i.e., low-frequency [LF] power [0.04–0.15 Hz], HF power [0.15–0.40 Hz], LF/HF ratio), and (3) *nonlinear* (complexity) index (i.e., sample entropy). We selected this multi-domain approach because time, frequency, and nonlinear metrics capture entirely distinct components of cardiac aR. Time domain metrics reflect overall variance, frequency domain metrics delineate specific sympathetic and parasympathetic contributions, and nonlinear metrics evaluate the underlying complexity and unpredictable dynamics of the cardiovascular system. Moreover, each metric provides a unique perspective on HRV, thus relying on a single domain metric would yield a limited or incomplete picture. By examining multiple metrics across domains simultaneously, this approach provides a more holistic, complementary assessment of autonomic function. Except for heart rate, all HRV metrics were log-transformed to produce normally distributed residuals. Generated variables were imputed in the final data file for further statistical analysis as described below.

Meaning of HRV metrics

CoV reflects the influence of the parasympathetic and sympathetic system on heart rate modulation. SDNN represents total HRV and is the successive time difference between successive Q waves on an electrocardiograph. RMSSD represents the peripheral nervous system and is considered a measure of vagally mediated change (reflecting parasympathetic activation). LF power is mainly coupled with variations in blood pressure and represents the modulation of both sympathetic and parasympathetic branches of the heart. HF power is associated with respiratory fluctuations and reflects parasympathetic activation. LF/HF ratio provides information about the balance between sympathetic and parasympathetic modulations. Sample entropy reflects the unpredictability of variations in consecutive RR intervals.

Sample size

The plan was to enroll 30 participants, which would yield a sample size of ≥ 25 after accounting for ≤ 20% attrition. However, recruitment stopped early when 25 participants had been enrolled due to restrictions put in place at the onset of the COVID-19 pandemic. It did not resume because of limited financial resources, slow recruitment, difficulties planning group sessions, and concerns that pandemic stress imposed on prospective participants could impact outcomes. After accounting for attrition (n = 5), the sample size for analysis was 20. This sample size was deemed sufficient for the intended hierarchical linear modeling (HLM), which can accommodate small sample sizes [52–54]. Moreover, the aim was to detect a preliminary signal of effect rather than establish efficacy or effectiveness.

Statistical analyses

No interim analyses were done. HLM (also known as multilevel modeling) was used to analyze outcomes after all participants had completed the study. HLM offers many advantages over traditional pre-post analyses with repeated measures, especially when dealing with longitudinal data and individual differences. Indeed, HLM was used because it: (1) maximizes statistical power and data completeness by accommodating missing data, (2) accommodates flexible data structures such as unequal assessment intervals, (3) accounts for the intra-subject

correlation inherent in repeated measurements, and (4) models *individual* trajectories to capture how participants differ in their rates and patterns of change over time. More information about the basic theoretical concepts of HLM and the basics of conducting HLM are available elsewhere [55, 56]. Briefly, a multistep procedure was followed for each outcome on a dataset that included the 20 participants who completed the study. Additionally, the data were graphed to display levels, trends, and variability of the data over time.

Step 1: Unconditional models

The first step was to ensure HLM was appropriate. An unconditional model (i.e., intercept only model) was tested. Only the outcome and the grouping variables (i.e., subject ID) were entered. The resulting p-values (<0.05) indicated significant variability in the outcomes *between* participants, thereby supporting the use of HLM to account for the nested data in subsequent analyses.

Step 2: Conditional models

The second step involved adding time, phase, and time-by-phase terms to estimate the overall rate of linear change over time, test if there was a significant change immediately upon YT exposure (i.e., right after the 1:1 YT session), and determine if the amount and direction of change differed between the baseline and YT intervention phases [54]. Time was coded linearly across the study period, starting at −3 for the first measurement occasion that occurred 3 weeks prior to the start of the YT intervention.

All models initially included random intercepts and slopes to account for possible differences in baseline levels and trajectories. Because our hypotheses focused strictly on fixed effects, nonsignificant ($p > 0.05$) random effects were subsequently removed to maintain a parsimonious model structure and prevent overparameterization [57]. This applied to variables with minimal slope variation (i.e., *trait ANS*, *mean heart rate*, *SDNN*, *CoV*, *sample entropy*, *LF power*, and *HF power*), where random slopes resulted in overparameterization without improving model fit. Consequently, more parsimonious random-intercept-only models were retained to account for participant-specific baseline differences. For each model, the intraclass correlation coefficient (ICC) was calculated by dividing the between-person variance by the total variance, which is the sum of the between- and within-person variances (i.e., $ICC = \tau00 / [\sigma2 + \tau00]$). An ICC of 0.45, for instance, implies that 45% of the variance in the outcome is due to person-to-person variation, whereas 55% is due to within-person variation across timepoints. Parameters were estimated using full information restricted maximum likelihood as it provides reliable estimates in the presence of missing data within small samples [58]. Accordingly, missing data were not imputed; all data from participants who initiated the YT intervention were analyzed. Additionally, a first-order autoregressive error structure was specified to account for autocorrelated errors (i.e., the error term [or residual] at one timepoint was correlated with the error term from a previous timepoint) [59]. Sensitivity analyses were conducted to examine the degree to which estimates were affected by different modeling decisions (e.g., allowing the Level-1 error covariance matrix to vary across participants, excluding two cases with discrepant patterns based on visual analysis of graphed data) [60]; no differences were observed. Descriptive and main data analyses were conducted using SPSS and R, respectively, and a significance level of $\alpha = 0.05$ was used. As this *proof-of-concept* analysis aimed to detect early signals of activity—rather than confirm efficacy—and prioritize sensitivity to any potential effects, no adjustments for multiple testing were made.

Results

Participants

A flow diagram, which includes items from the CONSORT extension for reporting of N-of-1 trials (CENT 2015) statement [61], reflects the flow of participants in the study (see Fig. 2). Eligible participants were enrolled from May 2017 to September 2019. Of the 120 adults referred or who self-referred, 25 were eligible and provided consent. Five withdrew after completing the first ($n = 4$) or second ($n = 1$) assessments, prior to commencing the YT intervention; their data were excluded from all analyses. No adverse events were recorded, either by the participants (via self-report), study staff, or yoga therapists (via observation). The overall attendance rate for the YT intervention was 99%, with participants attending 138 out of 140 possible sessions (calculated based on seven sessions per participant).

Detailed characteristics of the 20 participants are presented elsewhere [39]. In summary, the sample had a mean age of 55.74 years ($SD = 8.62$, range 42.26–73.46; $n = 2$ not reported) and was predominantly female (85.00%) and White/Caucasian (85.00%). Most (78.95%; $n = 1$ not reported) held a university/college degree, and 47.06% ($n = 3$ not reported) reported an annual household income of > $100,000 CAD. The most prevalent cancer type was breast (55.00%), followed by blood (10.00%) and other malignancies (e.g., eye melanoma, esophageal; 10.00%). At the time of diagnosis, clinical staging was evenly distributed across stages I (26.67%), II (26.67%), and III (26.67%), with a minority presenting at stage IV (6.67%); cancer staging was not appliable or missing for the remaining 13.33% ($n = 5$ not reported). The average time elapsed since diagnosis was 2.83 years ($SD = 3.45$,

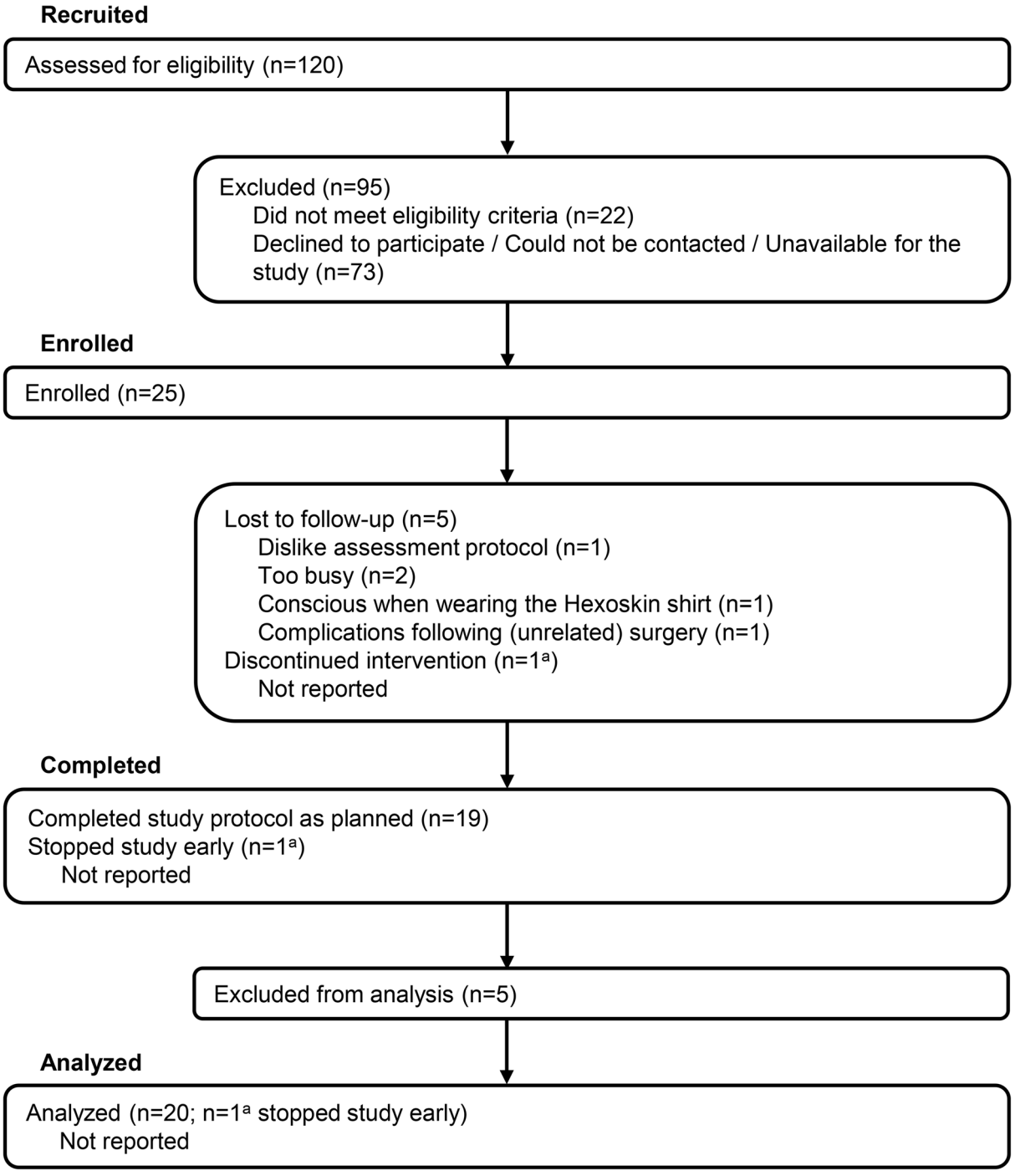

Fig. 2 Flow of participants in the study. [a]indicates same participant

range = 0.00–14.00; n = 1 not reported) and the average time since the completion of curative treatment was 1.50 years (SD = 2.08, range = 0.29–7.08; n = 3 not reported). Among the 17 participants who provided treatment dates, 64.71% were less than 1-year post-treatment. Regarding treatments modalities, the most frequently received treatments were surgery (80.00%), radiotherapy (75.00%), and chemotherapy (70.00%), while a smaller proportion underwent hormonal therapy (20.00%).

HRV and ANS functioning outcomes

Table 1 presents the HLM results, and a graphical illustration of the overall growth trajectory for each outcome is presented in Additional file 2. To facilitate comprehensive

Table 1 Results for hierarchical linear models ($N = 20$)

Outcomes	Fixed Effects				Random Effects				
	Estimates (SE)	95% CI	df	*p*	σ^2	$\tau_{00\ ID}$	$\tau_{11\ ID.Time}$	$\rho_{01\ ID}$	ICC
Self-Reported Outcomes									
State ANS									
a. Intercept	**55.02 (1.55)**	**51.95;58.09**	**44.70**	**< 0.001**	8.45	28.29	0.66	0.62	0.76
b. Time	**−1.41 (0.49)**	**−2.39;−0.43**	**90.94**	**0.005**					
c. Phase	**3.84 (1.17)**	**1.5;6.16**	**69.74**	**0.001**					
d. Time-by-phase	**1.49 (0.68)**	**0.1;2.83**	**73.50**	**0.031**					
Trait ANS									
a. Intercept	**43.77 (1.12)**	**41.55;45.98**	**36.86**	**< 0.001**	3.42	17.06	–	–	0.83
b. Time	−0.47 (0.29)	−1.05;0.10	92.01	0.107					
c. Phase	1.16 (0.74)	−0.31;2.63	92.03	0.122					
d. Time-by-phase	**0.88 (0.43)**	**0.03;1.73**	**92.10**	**0.042**					
Objective Outcomes									
Mean Heart Rate (bpm)									
a. Intercept	**71.91 (3.01)**	**65.95;77.86**	**48.45**	**< 0.001**	32.86	104.12	–	–	0.76
b. Time	1.13 (0.91)	−0.67;2.92	108.99	0.216					
c. Phase	−2.83 (2.25)	−7.28;1.62	109.01	0.211					
d. Time-by-phase	−0.99 (1.10)	−3.17;1.20	109.12	0.374					
Standard Deviation of Normal-to-Normal Intervals (SDNN; s)									
a. Intercept	**0.06 (0.01)**	**0.05;0.07**	**46.30**	**< 0.001**	0.00	0.00	–	–	0.77
b. Time	0.00 (0.00)	−0.01;0.01	109.05	0.171					
c. Phase	−0.01 (0.00)	−0.02;0.00	109.07	0.126					
d. Time-by-phase	−0.00 (0.00)	−0.01;0.00	109.17	0.087					
Coefficient of Variation (CoV; unitless)									
a. Intercept	**0.07 (0.01)**	**0.06;0.08**	**68.17**	**< 0.001**	0.00	0.00	–	–	0.65
b. Time	**0.04 (0.02)**	**0.00;0.06**	**109.04**	**0.045**					
c. Phase	**−0.01 (0.01)**	**−0.02;−0.00**	**109.08**	**0.030**					
d. Time-by-phase	**−0.01 (0.00)**	**−0.01;0.00**	**109.25**	**0.018**					
Square Root of the Mean Squared Differences of Successive Normal-to-Normal Intervals (RMSSD; s)									
a. Intercept	**0.03 (0.01)**	**0.02;0.04**	**38.86**	**< 0.001**	0.00	0.00	0.00	−0.96	0.84
b. Time	0.00 (0.00)	−0.00;0.00	109.51	0.942					
c. Phase	−0.00 (0.00)	−0.01;0.01	94.93	0.866					
d. Time-by-phase	−0.00 (0.00)	−0.01;0.00	98.77	0.450					
Sample Entropy (unitless)									
a. Intercept	**1.37 (0.07)**	**1.22;1.51**	**117.43**	**< 0.001**	0.04	0.02	–	–	0.37
b. Time	**−0.07 (0.03)**	**−0.13;−0.01**	**109.07**	**0.023**					
c. Phase	**0.17 (0.08)**	**0.02;0.32**	**109.17**	**0.024**					
d. Time-by-phase	0.07 (0.04)	−0.01;0.14	109.61	0.078					
Low-frequency/High-frequency (LF/HF) Ratio (%)									
a. Intercept	**3.43 (0.57)**	**2.29;4.57**	**89.38**	**< 0.001**	1.87	2.22	0.04	−1.00	–
b. Time	0.12 (0.22)	−0.32;0.55	113.63	0.601					
c. Phase	−0.60 (0.54)	−1.66;0.47	108.91	0.268					
d. Time-by-phase	−0.16 (0.26)	−0.68;0.36	108.96	0.534					
Low-frequency (LF) Power (s^2)									
a. Intercept	**0.11 (0.02)**	**0.08;0.14**	**89.62**	**< 0.001**	0.00	0.00	–	–	0.54
b. Time	−0.01 (0.01)	−0.02;0.00	109.02	0.057					
c. Phase	0.02 (0.01)	−0.01;0.05	109.08	0.143					
d. Time-by-phase	0.01 (0.01)	−0.00;0.02	109.34	0.201					

Table 1 (continued)

Outcomes	Fixed Effects				Random Effects				
	Estimates (SE)	95% CI	df	*p*	σ^2	$\tau_{00\ ID}$	$\tau_{11\ ID.Time}$	$\rho_{01\ ID}$	ICC
High-frequency (HF) Power (s^2)									
a. Intercept	**0.04 (0.01)**	**0.02;0.06**	**72.43**	**< 0.001**	0.00	0.00	–	–	0.63
b. Time	**−0.01 (0.00)**	**−0.02;0.00**	**109.11**	**0.006**					
c. Phase	**0.02 (0.01)**	**0.00;0.04**	**109.15**	**0.012**					
d. Time-by-phase	**0.01 (0.00)**	**0.00;0.02**	**109.34**	**0.011**					

Notes. Effect interpretations are as follows: Intercept: average levels upon starting the YT program, Time: linear slope, Phase: immediate shift in level between baseline and intervention phases, Time-by-phase: change in linear slope between baseline and intervention phases. Some cells are empty due to low/no variance. Abbreviations: estimate = unstandardized regression coefficient; *SE* = standard error; CI = confidence interval; df = degrees of freedom; *p* = p-value; σ^2 = within-person variance; τ_{00ID} = between-person variance; $\tau_{11ID.}$Time = random-slope variance (i.e., between-participant variance in slopes); ρ_{01ID} = slope-intercept correlation (i.e., how random intercepts and random slopes are related); ICC = intraclass correlation coefficient; bpm = beats per min ; s = seconds. Boldface indicates effect reached the statistically significant threshold of $p < 0.05$

reporting, bivariate correlations between the analyzed HRV metrics within each timepoint are detailed in Additional file 3. In summary, the intercept was the only fixed effect that reached the statistically significant threshold of $p < 0.05$ for ***mean heart rate***, ***SDNN***, ***RMSSD***, ***LF/HF ratio***, and ***LF power***, meaning that estimated intercepts differed significantly from 0.00. The estimated intercepts show the average values across the sample immediately after participants started the YT intervention (Table 1, Rows "a"). All fixed effects (intercept, time, phase, time-by-phase) reached the statistically significant threshold of $p < 0.05$ for remaining variables (***state ANS functioning***, ***CoV***, ***HF power***), except for ***trait ANS functioning*** (intercept and time-by-phase only) and ***sample entropy*** (intercept, time, and phase only); an overview of these fixed effects and their meaning is presented below.

State ANS functioning

All fixed effects reached the statistically significant threshold of $p < 0.05$. The fixed effect for the intercept reflects that, on average, participants scored 55.02 (*SE* = 1.55; scale range = 14–70) immediately after starting the YT intervention (i.e., right after the 1:1 YT session). The fixed effect for time demonstrates that, on average, participants' scores decreased by 1.41 (*SE* = 0.49) across each successive assessment. Moreover, the fixed effect for phase shows that, on average, participants' scores increased by 3.84 (*SE* = 1.17) immediately after their 1:1 YT session. Finally, the fixed effect for time-by-phase indicates a difference in the amount, but not direction, of change when comparing the rate of change before and after the YT intervention was introduced (time-by-phase = 1.49; *SE* = 0.68). This means that, on average, participants had a greater increase in state ANS functioning across successive assessments once the YT intervention was introduced.

Trait ANS functioning

The intercept and time-by-phase were the only fixed effects that reached the statistically significant threshold of $p < 0.05$. The estimates demonstrate that, on average, participants scored 43.77 (*SE* = 1.12; scale range = 18–54) immediately after starting the YT intervention (intercept) and had a greater increase in trait ANS functioning across successive assessments once the YT intervention was introduced (time-by-phase = 0.88; *SE* = 0.43), though the overall rate of change (time) did not reach the statistically significant threshold of $p < 0.05$.

CoV

All fixed effects reached the statistically significant threshold of $p < 0.05$. The estimates illustrate that, on average, participants had a CoV of 0.07 (*SE* = 0.01) immediately after starting the YT intervention (intercept), no change across successive assessments (time = 0.00; *SE* = 0.00), a decrease of 0.01 (*SE* = 0.01) immediately after their 1:1 YT session (phase), and a lesser decrease across successive assessment once the YT intervention was introduced (time-by-phase = − 0.01; *SE* = 0.00).

Sample entropy

All fixed effects (except time-by-phase) reached the statistically significant threshold of $p < 0.05$. The estimates show that, on average, participants had a sample entropy of 1.37 (*SE* = 0.07) immediately after starting the YT intervention (intercept), a decrease of 0.07 (*SE* = 0.03) across each successive assessment (time), and an increase of 0.17 (*SE* = 0.08) immediately after their 1:1 YT session (phase).

HF power

All fixed effects reached the statistically significant threshold of $p < 0.05$. The estimates reveal that, on average, participants had a HF power of 0.04 (*SE* = 0.01) immediately after starting the YT intervention (intercept), a decrease of − 0.01 (*SE* = 0.00) across each successive assessment (time), an increase of 0.02 (*SE* = 0.01) immediately after their 1:1 YT session (phase), and a greater increase across successive assessments once the YT intervention was introduced (time-by-phase = 0.01; *SE* = 0.00).

Discussion

Given the demanding and high-stress nature of cancer, research is needed to evaluate the effects of YT on HRV and ANS functioning after treatment to inform future research and supportive care. Though results are tentative and need to be corroborated by larger confirmatory studies, this early-phase, exploratory study offers an initial *proof-of-concept* that a YT intervention *may* affect multiple HRV metrics and self-reported ANS functioning after cancer treatment. We first discuss these results and then share our reflections on the challenges and the lessons learned while conducting this study because open communication about our experiences, which can be applicable to other studies of YT and/or HRV in oncology, is crucial to move the field forward.

Principal results provide preliminary support that YT warrants further, larger-scale investigation as the fixed effects for time, phase, and time-by-phase reached the statistically significant threshold of $p < 0.05$ for *state ANS functioning*, *CoV*, and *HF power*, as did the fixed effect for time-by-phase for *trait ANS functioning* and the fixed effects for time and phase for *sample entropy*. Notably, the observed shifts in these psychological and physiological outcomes following the introduction of YT suggests there *may* be an alteration in ANS regulation and stress resilience, offering a basis for future hypothesis testing. Presumably, the observed increase in HF power could reflect augmented parasympathetic (vagal) modulation of the heart, which would suggest an enhanced capacity for parasympathetic dominance, facilitating cardiovascular recovery and down-regulation of the physiological stress response. Moreover, the increase in sample entropy could indicate greater complexity and unpredictability in the inter-beat interval time series, which would suggest a more adaptable autonomic state, moving away from rigid or constrained system dynamics. Finally, while the observed decrease in CoV could potentially reflect improved physiological stability and less chaotic autonomic fluctuations, the precise physiological significance of CoV remains less clearly established in the literature compared to traditional HRV indices. Consequently, these specific findings should be interpreted with caution. Additionally, although these results and observations align with evidence from previous studies that different yoga styles are associated with improved HRV metrics and ANS functioning [33, 35–37], they are exploratory and require confirmation in larger confirmatory studies to establish whether YT can mitigate chronic stress loads by shifting the autonomic balance toward a more resilient, vagally-mediated state.

Thus, until such data are available, the observed psychological and physiological changes should be interpreted with caution for several reasons. First, the effect sizes were small and their clinical significance remains unclear without further research. Second, inferring therapeutic effects solely from changes in HRV metrics without clear physiological justification is impossible, and current physiological justifications discussed in research are not universally accepted as definitive. Instead, based on our results, the detected effects suggest that proceeding with future studies appears both possible and reasonable, wherein a goal should be to robustly establish therapeutic effects by linking changes in HRV metrics with meaningful, measurable clinical outcomes or improvements in specific symptoms. Notably, the collective results also suggest that the effects of YT on HRV metrics and self-reported ANS functioning may be nuanced, as nonsignificant ($p > 0.05$) effects were observed for some HRV metrics. These nonsignificant effects are consistent with the results of some studies [36] and may be simply due to a lack of statistical power. Accordingly, studies with larger sample sizes are required to ensure statistical power is achieved and confirm (or refute) the current results. However, beyond insufficient statistical power/small sample size and potential confounding variables, several other plausible explanations for the nonsignificant effects observed in this study exist. The following section consolidates these as they relate to participants, YT protocol and dosage, and HRV measurement and analysis.

Participants

One possible explanation may be the relatively subtle nature of autonomic dysfunction present in the sample. Participants in our study were not screened for features of ANS dysfunction (e.g., increased sympathetic activity, reduced cardiovagal baroreflex sensitivity, reduced HRV-derived indices of cardiac parasympathetic activity). It is possible that discerning effects of YT on certain HRV metrics is difficult if participants did not exhibit features of ANS dysfunction. More studies with samples exhibiting features of ANS dysfunction may help tackle this issue, though it is important to note that no normative values exist to classify dysfunction in this population. Alternatively, it is possible that chronic stress led to an upregulation of the sympathetic nervous systems—a key component of the body's "fight-or-flight" response—in the sample, which resulted in decreased HRV. Indeed, similar to the blunting response observed for cortisol in persons following adverse experiences [62–64], it is possible that chronic activation and exhaustion of the ANS led to decreased HRV and autonomic inflexibility that can be challenging to change in a short timeframe. Another possibility is that the effects of YT on certain HRV metrics may not be universally found in all participants such that positive and negative responses cancelled each other out. Beyond each participant's unique ANS profile, it is possible that characteristics such as time

spent practicing yoga, experiences of adverse events, lifestyle, and other elements (e.g., age, sex, gender, race, weight status, pain, psychological stress, smoking status, engagement in other integrative and complimentary therapies) could confound results. It is recommended that researchers examine these and other aspects that may moderate the effects of YT on HRV metrics and self-reported ANS functioning. Last, the effects of medication on ANS function are not fully understood and it is a difficult confounding factor to control for, especially as participants often require medication to maintain remission.

YT protocol and dosage

Certain practices (e.g., physical postures, breathing exercises) may be conducive to producing positive effects after only a short time. Other practices, such as those that foster self-awareness, may produce effects in the unexpected direction in the beginning as participants learn to become more aware of their inner thoughts, feelings, and sensations. As such, it is possible that a 7-week YT intervention may not provide enough time to see positive changes in stress reactivity. Indeed, the idea that stress-buffering benefits are more likely experienced after practicing yoga consistently for an extended period is not novel and has been discussed in recent research [21, 65, 66]. Further interventional studies are needed to elucidate if participants' responses to a longer YT intervention differs, indicating a possible need to extend the intervention. Relatedly, the dosage was limited to seven sessions. Several studies investigating the effects of different yoga styles on HRV have implemented intervention with eight or more sessions, with some, but not all, showing significant effects [67]. It is plausible that participants may require more sessions (over a longer period) to achieve stress-buffering effects. Furthermore, the YT intervention included individual and small group sessions, such that all participants started with one individual session and then progressed to six small group sessions. Whilst the therapists identified and responded to individual issues raised by the participants and invited them to share their experiences, each participant could not be *the* central focus and solely influence the content of the sessions. Finally, participants' expectations regarding peer experiences may not have been met, and some groups may have had better group dynamics than others. This raises another critical question for consideration, including the option of offering the intervention with 1:1 sessions only or the potential for stratifying group sessions by factors that could affect group dynamics such as diagnosis or age—if feasible. Regardless, with more research examining group-based sessions, participants' experiences within their group should be factored into future analyses to determine any influence on the trial outcomes, alongside qualitative explorations of participants' perspectives regarding the potential mechanisms of impact.

HRV measurement and analysis

ANS functioning, and as a result its measurement and interpretation, is complex and multifaceted. Accordingly, a strength of this study is the number of statistically derived HRV metrics analyzed to obtain a comprehensive assessment. Still, the variability in methodology, including assessment timing and duration, makes it difficult to compare effects with prior studies. Additionally, multiple intra- and inter-person factors can affect metrics, including behavioural factors (e.g., exercise, smoking, substance use, sleep), physiological factors (e.g., hemodynamics, breathing rate and depth, circadian rhythms, posture, obesity, metabolic syndrome, menstrual cycles, diurnal variations), psychological factors (e.g., emotional state, coping ability), health conditions (e.g., concomitant diseases, infection), and other factors (e.g., age, sex, genetics) [68–73]. Furthermore, although an overview of the specific measures of HRV are beyond the scope of the present study, the physiological interpretation of HRV metrics is a debated issue [74, 75], even with guidelines for HRV assessment and interpretation by the *Task Force of the European Society of Cardiology* and *North American Society of Pacing and Electrophysiology* [76, 77]. For example, LF power also has contributions from the parasympathetic nervous system and thus is not a 'pure' measure of sympathetic activity as initially theorized [78]. Additionally, the assessment protocol used in this study provided a measure of *resting* autonomic activity and does not capture how effectively the system can adjust when faced with actual stress stimuli. As HRV reflects the extent to which the brain and its central autonomic network can flexibly respond and react to stress stimuli [79, 80], future studies incorporating HRV measurement *in response* to stress-eliciting tasks (e.g., mental arithmetic, Trier Social Stress Tests) are necessary to provide direct insight into the flexibility and responsiveness of the ANS [12, 79], and thus better understand how YT may help people develop a more efficient stress response system. Overall, addressing these and previously mentioned considerations should be a key focus of future research.

Strengths and limitations

This study had many strengths. First, the YT intervention was delivered by therapists specially trained to provide YT. The therapists received regular supervision by the lead yoga therapist (AP) and additional consultations when needed. Second, we employed aR scales as a subjective self-report tool to assess participants' status of regulation for different autonomic functions and used

wearable garments as an objective physiological measure to assess HRV in a real-world setting. Considering the relative lack of use of physiological measures (compared to self-report) in studies on the wider practice of yoga, and the relative ease and unobstructive nature of the physiological data collection (compared to other methods used to assess HRV such as cardiac sympathetic imaging or muscle sympathetic nerve activity), this approach might add insight into the effects of YT (and yoga) on the mind and body. Third, in contrast with other common wearables that mostly provide pulse/heart rate rather than a full electrocardiogram waveform, HRV analysis was performed through electrocardiography, which is the gold standard for HRV assessment as it enables the calculation of beat-to-beat intervals with reliability to the millisecond level [81]. Fourth, by using a single-subject, unblinded experimental study with multiple baseline measures and HLM, our study accounts for any changes in participants' levels that occurred prior to the introduction of the YT intervention, thereby increasing the validity of the results since we allowed for, and modelled, both unstable changing levels and slopes over time and phases. This approach allowed us to predict the slopes and compare the data between the baseline and intervention phases, even when pre-existing trends existed. This highlights the need to continue incorporating multiple baselines assessments and using advanced statistical methods that account for baseline variability and trends in future studies.

Strengths notwithstanding, limitations should be considered, including the sample size. The multiplicity of analyses increases the risk of Type I errors (false positives) due to chance. Additionally, the small number of participants limits our ability to fully control for unmeasured covariates and diversity of factors (e.g., cancer types and stages), leading to residual confounding and greater imprecision in estimated effects. Second, we did not collect information on participants' current disease status (e.g., remission, stable, or recurrent disease). Given that ongoing disease activity can influence autonomic regulation and HRV, future studies should add these clinical variables into their sample descriptions and control for their potential confounding effects. Third, our sample was predominantly female, higher income, well-educated, White/Caucasian, and diagnosed with breast cancer, limiting generalizations to the broader population. To avoid limitations to external validity of the results and ensure supportive care interventions like YT do not unintentionally exacerbate disparities, comprehensive strategies that ensure diverse recruitment are crucial and should be prioritized in future studies. Example strategies include: (1) providing reimbursement costs for transportation, parking, and/or childcare to alleviate the burden on participants, (2) developing recruitment materials that reflect diversity and use representative imagery and inclusive language (e.g., use of images reflecting varying races, ethnicities, genders), (3) involving members from diverse communities in the review of recruitment materials, (4) ensuring all study materials and communication methods use simple, easily understood language and avoid complex medical jargon, (5) establishing study sites in underserved communities to minimize geographic/logistical barriers, and (6) offering flexible scheduling for data collection and intervention sessions to accommodate participants' competing demands (e.g., work, family responsibilities). Fourth, enrolled participants may differ from non-volunteers (e.g., having more interest in the topic, stronger motivation, more resources), making it difficult to draw universal conclusions. Fifth, we did not implement a controlled breathing protocol; the non-standardized breathing rate and depth during HRV recordings could have introduced confounding variables, potentially impacting the accuracy and interpretation of results. Sixth, some participants informally told members of the research team they were bored with the unstimulating, restrictive circumstance needed to have their heart rate and HRV assessed at rest. Whilst not surprising as our evolutionary history has ill-prepared us to sit and enter an 'empty' mental and physical state, there is the possibility that sitting quietly made participants vulnerable to a heightened awareness of their daily worries, social demands, and symptoms (e.g., pain, fatigue). Seventh, though a partnership between researchers and the CHI facilitated an iterative development of the study and enabled the successful implementation of the intervention and study in the community, like many other studies, the results may be context specific. Eighth, music was played during the YT sessions which can be considered a confounder because it is an external stimulus that can independently influence participants' physiological and psychological responses. Ninth, the psychometric properties of the different measures could not be reported robustly due to insufficient sample size for reliable analysis. Tenth, scheduling participants' seven assessments at consistent times proved unfeasible in some cases; this could have introduced intra- and inter-person variability and therefore had an influence on the results. A final limitation of this early-phase, single-subject design is the absence of a control (or comparison) condition. While this design is highly valuable for intensive, individualized evaluation during the exploratory stages of an intervention, it prevented us from disentangling the specific effects of the YT intervention from potential time-related maturation, historical influences, or other contextual factors. Consequently, the findings should be interpreted as preliminary, intended to establish a proof-of-concept and inform the direction of future research rather than to establish causality. Subsequent studies could implement

a randomized controlled trial or a waitlist-controlled design to rigorously compare the YT intervention group against a control condition.

Conclusions

The primary goal of this early-phase, exploratory study was to determine if a YT intervention may impact HRV and ANS functioning among adults after cancer treatment. Although the results should be interpreted cautiously and limitations should be borne in mind, they offer early, hypothesis-generating observations on how a 7-week YT intervention may impact HRV and ANS functioning. Considering the early signs, the findings suggest the intervention warrants further, more extensive investigation to examine if YT favourably affects HRV and ANS functioning in larger confirmatory studies. Additionally, this study provided insight into several considerations for future studies in this emergent field. It is recommended that researchers employ a control condition, recruit larger and more diverse study samples, examine varying dosages with varied formats (e.g., 1:1 sessions only, mixed 1:1 and group sessions), and include an evaluation of the long-term effects of YT on outcomes. Finally, further research is necessary to understand what aspects of YT may lead to stress buffering effects. Such research would be strengthened by including qualitative insights from participants about their YT experiences and what they feel causes the effects.

Abbreviations

ANS	Autonomic nervous system
aR	Autonomic regulation
CENT	CONSORT Extension for reporting of N-of-1 Trials
CHI	Centre for Health Innovation
CLARIFY	CheckList stAndardising the Reporting of Interventions For Yoga
CONSORT	Consolidated Standards of Reporting Trials
CoV	Coefficient of variation
HF	High frequency
HLM	Hierarchical linear modelling
HRV	Heart rate variability
ICC	Intraclass correlation coefficient
LF	Low-frequency
M	Mean
RMSSD	Square root of mean squared differences of successive normal-to-normal intervals
SD	Standard deviation
SDNN	Standard deviation of normal-to-normal intervals
SE	Standard error
YT	Yoga therapy

Supplementary Information

The online version contains supplementary material available at https://doi.org/10.1186/s13030-026-00367-x.

Supplementary Material 1: CONSORT checklist

Supplementary Material 2: Model prediction figures for heart rate variability (HRV) and self-reported autonomic nervous system (ANS) functioning outcomes

Supplementary Material 3: Pearson correlation coefficients (*r*) between heart rate variability (HRV) metrics within timepoints

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Author contributions

JB and DS conceived the study. JB, AW, AP, AS, and DS made substantial contributions to the conception and design of the study. AP made substantial contributions to the conception and design of the yoga therapy intervention, as well as oversaw the delivery of the yoga therapy intervention. JB, AW, JH, AP, EC, and DS participated actively in the execution of the study reported on. JB, CH, and NP performed different steps in data processing and analysis. JB drafted the manuscript. JH contributed to the original draft of the manuscript and helped prepare the manuscript for submission. All authors critically reviewed the manuscript for intellectual content and approved the final version to be published.

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Data availability

The data cannot be shared as participants were assured that their data would be kept private and confidential to the extent permitted by law and that only the research team would have access to their data.

Declarations

Ethics approval and consent to participate

Approval was granted by the University of Ottawa (no.: H01-17-04, March 17, 2017) and the Canadian College of Naturopathic Medicine (no.: CCNMREB016, February 28, 2017). Written informed consent was obtained from all participants prior to their participation.

Consent for publication

Informed consent was obtained from all participants for results to be published.

Competing interests

Jennifer Brunet (corresponding author) reports financial support was provided by Canadian CAM Research Fund. While declared for transparency, the provision of financial support did not influence the research results, methodology, or interpretation. Andrew Seely from the Ottawa Hospital Research Institute (OHRI) is a patent holder, Founder/CEO, and shareholder of Therapeutic Monitoring Systems (TMS) Inc.—a company focused on commercialization of variability-derived clinical decisions support tools developed in OHRI's Dynamical Analysis Laboratory. Christophe Herry is one of the inventors related to this patent. Neither A. Seely nor C. Herry report any conflict of interest directly related to the subject matter of this manuscript. Remaining co-authors declare no financial interests/personal relationships that may be considered as potential competing interests.

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