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The relationship between resting heart rate variability and erectile tumescence among men with normal erectile function

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Abstract

Introduction—Individuals with erectile dysfunction have been shown to display lower heart rate variability (HRV), suggesting dysregulation of cardiac autonomic function. No studies have explored whether HRV is predictive of erectile response among men with clinically normal erectile function.

Aim—To examine associations between resting HRV and objective measures of genital response (i.e., resting penile circumference; erectile tumescence) and self-reported sexual function.

Methods—The sample comprised 59 male community volunteers (mean age = 20.15 years; SD = 2.52) selected from the control conditions of two previously published studies. Participants reported erectile function in the normal range (scoring ≥ 26 on the International Index of Erectile Function [IIEF]) and had no history of cardiovascular disease or myocardial infarct. During a laboratory visit, self-report, anthropometric, cardiovascular, and electrocardiographic data were assessed, as well as resting penile circumference and erectile tumescence in response to viewing an erotic film.

Main Outcome Measures—Resting penile responses, erectile tumescence (circumferential change via penile plethysmography), self-reported sexual function per the IIEF, and both time-domain (standard deviation of beat-to-beat [NN] intervals [SDNN], square root of the mean squared difference of successive NN intervals [RMSSD], and percent of NN intervals for which successive heartbeat intervals differed by at least 50 msec [pNN50]) and frequency-domain (low frequency [LF], high frequency [HF], LF/HF ratio) parameters of HRV were assessed.

Results—Higher resting HF power and lower resting LF/HF ratio were associated with greater erectile tumescence. There were marginally significant positive associations between mean NN interval and pNN50 and penile tumescence. HRV was not associated with self-reported sexual function or with resting penile circumference.

Conclusions—Results suggested that, among men without erectile dysfunction, relatively elevated parasympathetic tone was predictive of larger erectile tumescence. Limited variance in sexual function scores may have accounted for the lack of association between HRV and IIEF scores.

Keywords

heart rate variability; cardiac autonomic function; sexual arousal; erectile tumescence; erectile function; erectile physiology

INTRODUCTION

The physiology of penile erection is a complex process involving mechanisms from several organ systems operating in concert. Erectile tumescence is primarily under the control of the parasympathetic nervous system. During nonadrenergic, noncholinergic neurotransmission, nitric oxide is released, which is the primary neurotransmitter mediating penile smooth muscle relaxation resulting in genital engorgement [1–3]. Erectile detumescence, on the other hand, is modulated by the sympathetic nervous system via the release of norepinephrine and activation of postsynaptic α 1-adrenergic receptors, which deactivates veno-occlusive mechanisms returning the penis to its flaccid state [4, 5]. These autonomic processes are controlled by the central nervous system and by the peripheral nervous system via spinal erection centers that contain sympathetic nerves from the 11th thoracic to the 2nd lumbar spinal segments and parasympathetic nerves from the 2nd to 4th sacral spinal cord segments [5].

The fact that erectile hemodynamics and cardiac function are both largely under the influence of the autonomic nervous system (ANS), has led to the hypothesis that disruptions in cardiac autonomic balance may serve as an underlying mechanisms responsible for the pathophysiology of penile erection. These ANS alterations, typically reflected as increased sympathetic and decreased parasympathetic activity [6], have been associated with reduced heart rate variability (HRV). HRV is a predictor of health and longevity, and is associated with both physical and mental health processes [7, 8], while also serving as an indicator of ANS and prefrontal brain function integration [9]. HRV is a general proxy for cardiac health; elevations in HRV (evidenced by high variability in beat-to-beat intervals) represent healthy cardiac function, whereas reductions in HRV (low inter-beat variability), leaves the heart vulnerable to arrhythmia and sudden death [10]. HRV is capable of noninvasively assessing vagal tone and may serve as a unique tool to assess neurogenic erectile dysfunction.

To this end, there has been a small, yet growing, body of literature examining the association between HRV and erectile health. These studies have generally shown that individuals with erectile dysfunction (ED), compared to healthy controls, display a relative diminution of parasympathetic activity and an increase in sympathetic activity of the ANS [11–16]. These sympathovagal disruptions have been typically reflected as greater high-frequency to low-frequency ratios (a HRV parameter reflecting the balance of ANS; higher values denote sympathetic dominance and cardiac dysregulation, whereas lower values represent parasympathetic dominance) among patients compared to controls [11–16]. Taken together, these results point to the possibility that HRV may have clinical utility in distinguishing those with normal erectile function from those with ED.

These aforementioned studies have helped to enhance our understanding of the multifaceted processes involved in erectile function. However, there are several aspects regarding the link between cardiac and erectile health that remain unanswered. To the author's knowledge, no studies have examined whether parameters of HRV are predictive of erectile response among men with clinically normal erectile function. Moreover, no studies have examined associations between HRV and genital responses assessed physiologically (via continuous changes in penile tumescence). Examining the potential link between cardiac autonomic function and erectile physiology among nonclinical men may help to further elucidate mechanisms underlying the physiology and pathophysiology of male sexual arousal.

AIM

The present study examined associations between cardiac autonomic function (assessed via HRV) and both objective measures of penile response (i.e., resting flaccid penile

circumference; magnitude of penile tumescence when sexually aroused) and self-reported sexual function, among sexually functional young men without a history of cardiovascular disease (CVD) or myocardial infarct (MI). HRV was chosen as an outcome measure, given that this parameter is a marker of sympathovagal balance, which is a chief underlying mechanism of erectile response [17].

METHOD

Participants

Participants were 59 community volunteers selected from the control conditions of two experiments previously completed and published elsewhere [18, 19]. Participants were recruited via community and online advertisements. Inclusionary criteria included being at least 18 years of age, being currently sexually active, and reporting healthy erectile function (scoring ≥ 26 on the International Index of Erectile Function (IIEF) [20], a well-established cutoff to distinguish those with and without probable erectile dysfunction [21]). Exclusion criteria for both studies were as follows: (i) use of medications or report of medical conditions known to affect sexual or vascular functioning; (ii) current self-reported sexual complaints within domains of sexual desire, sexual arousal, or sexual pain, and/or a history of treatment for sexual dysfunction; (iii) self-report of a sexually transmitted infection; (iv) self-report of an active psychiatric condition such as a psychotic-spectrum disorders, a bipolar spectrum disorder (i.e., bipolar I/II disorder, cyclothymic disorder, bipolar disorder not otherwise specified), eating disorders (such as anorexia nervosa and bulimia), depression, and anxiety disorders (such as panic disorder and posttraumatic stress disorder); and (v) being a current smoker. Other disqualifying criteria specific to the Harte and Meston study [18], which examined the effects of acute nicotine intake on sexual arousal, included: having a known allergy to nicotine, currently taking any medication that would adversely interact with nicotine (e.g., bupropion), and presence of a medical condition that could make nicotine administration unsafe (e.g., history of MI, stroke, heart arrhythmias, angina, uncontrolled hypotension or hypertension).

Procedure

Data from the two studies included in this report had different aims, however, both studies were conducted within the same laboratory and all study procedures were identical. In brief, participants completed a preliminary telephone interview, during which they were screened for inclusion/exclusion criteria and were given a detailed description of the study. Screenings were conducted by a trained research assistant, and reviewed by the first author. All participants were asked to refrain from using any illicit substances and/or alcohol before entering the laboratory. Upon arrival to the laboratory, all study procedures were reviewed and participants provided written, informed consent. Self-report data were then collected (socio-demographic information, medical history, alcohol and tobacco use, and erectile function), as well as anthropometric (height and weight), cardiovascular (systolic and diastolic blood pressures), electrocardiographic (HRV), and sexual arousal data (i.e., erectile tumescence). After receiving detailed instruction on the nature and operation of the penile plethysmograph, participants placed the genital gauge themselves, positioned mid-shaft on the penis, while sitting upright in a comfortable chair in a quiet, private, internally locked room within the laboratory. Electrocardiographic (ECG) and sexual arousal data were collected simultaneously while participants viewed audiovisual stimuli. The films used in both studies [18, 19] consisted of an initial 3-minute non-sexual segment (documentary film presentation), immediately followed by an 8-minute erotic film presentation depicting heterosexual penile-vaginal intercourse. The two film segments (neutral, erotic) within each film sequence were always presented in the same order. ECG data was collected during spontaneous breathing for all participants. For the purposes of the current study, only ECG

data from the initial 3-minute baseline period were examined. Participants were compensated between \$15 and \$30 (depending on the number of sessions completed for the particular study). The specific experimental procedures of both studies can be found in their respective manuscripts [18, 19]. Due to randomization of participants into control sessions (included here) and experimental sessions (not included here), some of the participants ($n = 30$) had previously completed a similar testing session, while others were naïve to the procedures ($n = 29$)¹. Both study protocols were approved by the university Institutional Review Board.

MAIN OUTCOME MEASURES

Electrocardiography

Electrocardiographic signals were assessed using a three-channel electrocardiograph (ECG) and were collected at a rate of 80 samples/second, low-pass filtered (to 0.5 Hz), digitized (40 Hz), and recorded using a Model MP100WS data acquisition unit (BIOPAC Systems, Inc., Santa Barbara, CA, USA) and the software package AcqKnowledge III, Version 3.73 (BIOPAC Systems, Inc.). A series of inter-beat intervals (based on detection of QRS complexes, part of the ECG wave representing ventricular depolarization) were collected manually using the AcqKnowledge peak finder function, and artifacts were identified and removed manually. After cleaning ECG recordings, mean inter-beat interval (NN) and mean heart rate (HR) were derived. Kubios HRV Analysis Software (Biosignal Analysis and Medical Imaging Group, University of Kuopio, Kuopio, Finland) was used to calculate both time- and frequency-domain HRV indices. Time-domain measures included the standard deviation of NN intervals (SDNN), the square root of the mean squared difference of successive NN intervals (RMSSD), and the percent of NN intervals for which successive heartbeat intervals differed by at least 50 msec (pNN50). Fast Fourier transform procedures were used to derive the spectral distribution, which comprised the frequency-domain parameters of HRV. Indices included (in msec²) low-frequency (LF) power (.04 – .15 Hz), high-frequency (HF) power (.15 – .40 Hz), and the ratio of these two indices (LF/HF), which reflected sympathovagal balance [22].

Penile Tumescence

Penile tumescence was assessed via penile plethysmography using a mercury-in-rubber strain gauge (Hokanson, Inc., Bellevue, WA, USA) to capture continuous changes in penile circumference (recorded in mm). The signal was sampled at a rate of 80 samples/second, bandpass filtered (to 0.5 Hz), digitized (40 Hz), and recorded using a Model MP100WS data acquisition unit (BIOPAC Systems, Inc.) and the software package AcqKnowledge III, Version 3.73 (BIOPAC Systems, Inc.). Data were z-transformed within participants to reduce the confounding effect of baseline penile circumference on associated circumferential changes during sexual arousal [23].

Sexual Function

The IIEF [20] was administered to ensure that men were within the normal range of erectile functioning. The IIEF is a 15-item measure assessing five domains of sexual function: erectile function (six items), orgasmic function (two items), sexual desire (two items), intercourse satisfaction (three items), and overall satisfaction (two items). The IIEF is the most widely used psychometric index of self-reported erectile function, and demonstrates

¹There were no associations between protocol familiarity (i.e., naïve vs. prior testing) and any HRV parameter, nor were there any relations between protocol familiarity and objective (i.e., resting penile circumference, penile tumescence) and subjective (i.e., IIEF) erectile measures.

good psychometric properties [20]. Internal consistency of this measure for the current study was acceptable (α s = .62 – .90).

STATISTICAL ANALYSIS

For each participant, change scores were calculated for physiological sexual arousal by subtracting the value of the mean arousal response throughout neutral film presentation (while sexually unaroused) from the mean arousal response throughout the erotic film presentation (sexually aroused state). The predictive value of resting parameters of HRV in estimating both resting penile circumference and subsequent penile tumescence responses (when sexually aroused) was examined by means of linear regression analyses. These analyses were repeated with IIEF erectile function score as the criterion variable. Relationships between resting penile circumference and resting HRV parameters were additionally explored by means of creating median splits on the distribution of data within each HRV index. These two resulting groups (i.e., “high” and “low”) for each HRV parameter were compared via independent samples *t*-tests with both *z*-transformed and raw (in cm) penile circumference values as the dependent variables. Analyses were performed using SPSS statistical software version 19.0 (SPSS Inc., Chicago, IL, USA). All tests were two-tailed with an alpha level set at .05.

RESULTS

Participant Characteristics

Please see Table 1 for sociodemographic and descriptive characteristics. The total sample ($N = 59$) ranged in age from 18 to 27 years with a mean age of 20.15 years ($SD = 2.52$). The majority of the sample was White (55.9%); breakdowns of other races/ethnicities were as follows: 8.5% Black/African-American; 23.7% Latino; 8.5% Asian; and 3.4% “other.” No participants reported a current or lifetime medical condition, and therefore none reported a history of MI or current CVD. Nine participants were taking medications (antihistamine, $n = 4$; bacteriostatic antibiotic, $n = 2$; dextroamphetamine and amphetamine [Adderall], $n = 3$)².

Potential Covariates

A zero-order correlation matrix (i.e., a table of inter-correlations between all variables in question [24]) was first constructed to determine whether variables that have previously shown to be associated with HRV, penile tumescence, and erectile function should be entered as covariates into the subsequent linear regression models. As such, age, alcohol use, body mass index, resting HR, and resting diastolic and systolic blood pressures were included, as well as all HRV parameters (predictors), objective genital indices (resting penile circumference, erectile tumescence responses), and self-reported erectile function (criterion variables). None of these variables showed significant relations with either the predictor or criterion variables, and therefore none were entered as covariates into subsequent models.

Associations between Resting HRV and Resting Penile Circumference

Linear regression analyses revealed that none of the resting HRV parameters predicted resting penile circumference (β s = <.001 – .07, t s = .01 – 1.44, P s = .16 – .99, adj R^2 = .01 – .02). Additionally, when comparing those with relatively low and high levels of HRV (dichotomized via median split), there were no differences in resting penile circumference (*z*-transformed circumference values: t s = -1.33 – .87; P s = .19 – .82; d s = .06 – .36; raw

²All results remained unchanged when excluding individuals taking dextroamphetamine and amphetamine.

circumference values: $t_s = -1.63 - 1.50$; $P_s = .14 - .96$; $d_s = .01 - .38$) for any of the HRV parameters (please see Supplementary Table).

Associations between Resting HRV and Subsequent Erectile Tumescence Responses

Results of the linear regression analyses revealed that HF power and the LF/HF ratio significantly predicted magnitude of genital arousal responses (see Table 2). Specifically, HF power was positively associated with physiological sexual arousal responses ($\beta = .28$, $t = 2.22$, $P = .03$, adj $R^2 = .06$), whereas the LF/HF ratio was negatively associated with penile tumescence ($\beta = -.32$, $t = -2.56$, $P = .01$, adj $R^2 = .09$). There was a statistical trend for mean NN interval ($\beta = .24$, $t = 1.83$, $P = .07$, adj $R^2 = .04$) and pNN50 ($\beta = .23$, $t = 1.75$, $P = .07$, adj $R^2 = .03$) in predicting magnitude of physiological sexual arousal responses, and these relationships were both positive. Mean HR, SDNN, RMSSD, and LF were not predictive of sexual arousal ($P_s: .21 - .98$; adj $R^2: .001 - .02$); however all relationships were in the expected direction (lower HR and higher SDNN, RMSSD, and LF associated with larger penile tumescence).

Associations between Resting HRV and Self-Reported Erectile Function

Linear regression analyses revealed that none of the HRV parameters served as significant predictors of self-reported erectile function ($\beta_s = .01 - .11$, $t_s = .18 - 1.20$, $P_s = .24 - .75$, adj $R^2 = .01 - .02$).

DISCUSSION

The present study examined associations between cardiac autonomic function (assessed via HRV) and both objective measures of penile response (i.e., resting flaccid penile circumference; magnitude of penile tumescence when sexually aroused) and self-reported sexual function among sexually functional healthy men. Results indicated that, among the subset of HRV parameters examined, higher resting HF power and lower resting LF/HF ratio were associated with greater increases in erectile tumescence in response to sexual stimuli. Additionally, there were marginally significant positive associations between mean NN interval and pNN50 and penile tumescence. That is, higher resting NN interval and greater resting pNN50 values were predictive of larger erectile responses. Taken together, results suggested that relatively elevated parasympathetic tone (i.e., parasympathetic dominance as evidenced by higher HRV parameters and lower LF/HF ratios) – a proxy for healthy cardiac autonomic function – was prognostic of superior erectile responses assessed physiologically. These findings were in line with prior studies showing that healthy controls, compared to individuals with ED, display a relative enhancement in parasympathetic activity and a diminution in sympathetic activity [11–16]. Furthermore, these findings add to the growing body of literature delineating the relationship between resting HRV and sexual health more broadly. That is, research has demonstrated that resting HRV is associated with frequency of penile-vaginal intercourse (PVI) [25, 26] (and frequency of orgasm resulting specifically from PVI [27]), which in turn is related to enhanced health and relatedness, as well as to reduced risk of sexual dysfunction [27–30].

Although HRV parameters were predictive of laboratory measures of erectile tumescence, resting HRV was not associated with self-reported indices of sexual function. This may have been due to the nature of the instruments used to assess erectile function. That is, penile plethysmography is a robust and sensitive tool capable of assessing dynamic fluctuations in erectile tumescence, and therefore may be well suited to capture subtle, albeit statistically significant, covariations between erectile capacity and HRV. Given that all participants in the current study demonstrated normal erectile function, distribution of self-reported erectile function scores (per the IIEF) were restricted to a relatively narrow range (26 – 30), which

likely reduced statistical power to observe statistically significant effects. HRV was also not associated with resting penile circumference, which may highlight the possibility that HRV's role in penile vasculature is primarily with respect to tumescence (i.e., during sexual arousal) and not resting genital tone. However, this is purely speculative and further research is necessary to delineate these processes further.

Strengths of the current study included: (i) both self-reported (i.e., IIEF scores) and objective physiological (i.e., penile plethysmography) outcome measures as criterion variables to examine the predictive relationship between HRV and erectile response; (ii) examination of a variety of time- and frequency-domain HRV parameters; and (iii) exclusion of individuals with a history of MI, CVD, and cardiovascular medication use, all of which have been associated with cardiac autonomic imbalance [31, 32]. Despite this investigation's novel findings, several study limitations warrant mention. First, the need to exercise caution in making direct casual inferences must be acknowledged, given the cross-sectional nature of the study design. The association between HRV and erectile response among sexually functional men warrants further investigation in the form of longitudinal studies to establish temporality of a potential causal link between these variables. Second, spontaneous breathing was not controlled for in the present study (i.e., via paced or timed breathing). Studies have shown that respiratory parameters can influence HRV (via the respiratory sinus arrhythmia mechanism [33]) independent of changes in cardiac autonomic regulation [34]. Therefore the potential covariation between sexual arousal and changes in depth and/or rate of breathing could not be ascertained, and therefore results of HRV parameters should be interpreted cautiously. However, it should also be noted that SDNN and RMSSD HRV parameters are fairly resistant to the effects of changes in breathing patterns [35]. Third, it should be emphasized that HRV provides only an indirect measure of cardiac ANS function and should be regarded as a generally qualitative, not quantitative, proxy for cardiac autonomic regulation [34]. Furthermore, HRV reflects complex interactions between sympathetic and parasympathetic nerve fibers, mechanical factors, and other sinoatrial mechanisms [34], and therefore HRV does not perfectly capture clear divisions of cardiac autonomic activity with respect to ANS branches. The fourth limitation was with regard to the generalizability of the participant sample; African-American individuals were under-sampled compared to the general population of the United States [36]. Finally, all participants were characterized as having normal erectile function via self-report per the IIEF, rather than via medical evaluation. Moreover, this assessment tool was originally designed to assess ED [20], and therefore its psychometric properties may not directly translate to younger men [37] with normal erectile function. However, this was offset by the fact that the IIEF has been adopted as the "gold standard" measure for brief evaluation of self-reported erectile functioning and has been used in more than 50 clinical trials [38], as well as numerous research studies involving young nonclinical populations. Finally, it should be noted that, although penile plethysmography provided an objective quantitative index of erectile response, its use should not be construed as providing prognostic value as to the nature of "normal" versus "abnormal" erectile responding.

CONCLUSIONS

In conclusion, this was the first study to examine whether parameters of HRV were predictive of both objective and subjective indices of erectile response among men with normal erectile function. Results indicated that cardiac autonomic tone was associated with penile tumescence, whereby parasympathetic dominance predicted greater erectile response. Although in need of replication and further study, findings from the current investigation further point toward the potential underlying role of cardiac autonomic function in the physiology of penile erection.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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TABLE 1

Characteristics of the Participant Sample

Characteristic	<i>M</i>	<i>SD</i>	<i>n</i>	%
Age (years)	20.15	2.52		
Education (years)	13.38	1.66		
Ethnicity				
White/Caucasian			33	55.9
Black/African-American			5	8.5
Latino			14	23.7
Asian			5	8.5
Other			2	3.4
Marital status				
Single			56	94.9
Married			3	5.1
Alcohol use (drinks/week)	7.22	9.71		
Sexual function *				
Erectile function	28.76	1.50		
Orgasmic function	9.10	1.62		
Sexual desire	8.02	1.41		
Intercourse satisfaction	11.71	1.89		
Overall satisfaction	7.90	1.76		
Medication use			9	15.3
Antihistamine **			4	44.4
Bacteriostatic antibiotic **			2	22.2
Dextroamphetamine and amphetamine **			3	33.3
Height (m)	1.78	.10		
Weight (kg)	75.21	10.65		
BMI (kg/m ²)	23.70	2.52		
Cardiac function				
Resting HR (bpm)	74.36	12.83		
Systolic BP (mm Hg)	122.39	10.99		
Diastolic BP (mm Hg)	73.46	9.28		

Note. BMI = body mass index; BP = blood pressure; bpm = beats per minute; mm Hg = millimeters mercury; HR = heart rate; M = mean; SD = standard deviation.

* per the International Index of Erectile Function [20].

** Percentages calculated among those reporting current medication use ($n = 9$).

TABLE 2

Associations between Resting HRV Parameters and Subsequent Erectile Tumescence Responses

Cardiac parameter	B	SE B	β	<i>t</i>	<i>P</i> -value	Adjusted <i>R</i> ²
Heart rate (bpm)	-.01	.01	-.14	-1.04	.30	.001
NN interval (msec)	.001	<.001	.24	1.83	.07	.04
SDNN (msec)	<.001	.002	.01	.03	.98	.02
RMSSD (msec)	.002	.002	.12	.94	.35	.002
pNN50 (%)	.01	.01	.23	1.75	.07	.03
LF power (msec ²)	<.001	<.001	.17	1.28	.21	.01
HF power (msec ²)	<.001	<.001	.28	2.22	.03	.06
LF/HF (msec ²)	-.15	.06	-.32	-2.56	.01	.09

Note. B = unstandardized beta; (β = standardized beta; Bpm = beats per minute; HF = high frequency power; HRV = heart rate variability; LF = low frequency power; NN = inter-beat interval; pNN50 = percent of NN intervals for which successive heartbeat intervals differed by at least 50 msec; RMSSD = square root of the mean squared difference of successive NN intervals; SDNN = standard deviation of NN intervals; SE B = standard error of the unstandardized beta value.