Time-Frequency Analysis of Cardiovascular Variability during Two Types of Continuous and Linearly Increasing Isometric Exercise

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Abstract

To characterize the effect of isometric exercise (IE) intensity on the cardiovascular autonomic variables (CVAV), we assessed the continuous relationships between force and the high frequency power of RR intervals (HF_{RR}), low to high frequency ratio (LF_{RR}/HF_{RR}) and low frequency power of systolic pressure (LF_{SP}), estimated by a time-frequency distribution (TFD). Thirty five healthy subjects performed continuously increasing static handgrip (HG) and static leg extension (LE) until maximal force (MF). Main findings were: 1) strong correlations between %MF and $\ln HF_{RR}$; 2) threshold phenomena around 65%MF in %MF vs. LF_{SP} and LF_{RR}/HF_{RR} relations; and 3) greater effects on CVAV of LE than HG ($p<0.001$). Combining continuously increasing IE intensity with a TFD allows to obtain continuous relations between CVAV and intensity in the widest range, which show strong correlations, threshold phenomena and greater autonomic responses in LE.

1. Introduction

Although there is some evidence that the arterial pressure (AP) and heart rate (HR) increments produced by isometric exercise (IE) are proportional to the contraction intensity, the degree of correlation between effort and cardiovascular response has not been established [1,2], because the usual IE protocols consist on a single contraction of low to medium intensity (typically 30% of the maximal voluntary contraction, MVC), sustained for several minutes [3,4]. Given the inverse relationship between contraction intensity and endurance time, the response of the cardiovascular autonomic variables (CVAV) to high IE intensities is not well characterized.

Spectral analysis of cardiovascular variability (CVV) is a powerful noninvasive procedure for the quantitative assessment of autonomic activity [5]. The good performance of the high frequency component of RR intervals (HF_{RR}) as an index of vagal activity, the low to high frequency ratio (LF_{RR}/HF_{RR}) as marker of sympathovagal balance and of the low frequency power of systolic pressure (LF_{SP}) as a measure of the sympathetic modulation of the vascular tone is well documented [5]. However, there are few studies that have applied the spectral analysis of CVV during IE [6], and they have used spectral estimation methodologies that require stationarity of the signals [4,7,8]. Information regarding the use of time-frequency distributions (TFD) to analyze CVV during IE is not available.

To contribute to the solution of the aforementioned issues, we assessed the continuous relationships between spectral indexes of CVV, estimated by a TFD, and the contraction intensity during two types of continuous and linearly increasing IE, static handgrip (HG) and static leg extension (LE).

2. Methods

2.1. Subjects

Thirty five young, healthy, nonsmoking and sedentary subjects, 25 men and 10 women, participated. Their age, height and weight were 22.4±2.7 years, 167±8 cm and 66.2±11.0 kg respectively. Their informed consent was requested to participate. This study was approved by the ethics committee of our university.

2.2. Protocol

In a first visit to the laboratory the health status of the subjects was evaluated and they were trained to correctly execute IE. In a second visit, subjects performed static HG and LE in sitting position, resting for at least 30 min. between trials. Each session consisted on three successive stages: 1 min. of control; maneuver, subject performing incremental IE at a rate of 0.21 kg/s until exhaustion, where the maximal force (MF) was attained; and recovery for 2 min. Subjects linearly increased their force at the target rate aided by visual feedback.

2.3.Recorded variables and signal acquisition

ECG was detected at the thoracic bipolar lead CM5 using a bioelectric amplifier (Biopac Systems). Beat-to-beat arterial pressure was recorded by Finapres (Ohmeda). Respiratory movements were recorded with a pneumograph (Biopac Systems). Contraction force was measured with two handgrip dynamometers (Stoelting), one mechanically adapted to a chair to measure LE force. All signals were digitized at a sampling rate of 500 Hz via an acquisition and display system (Biopac Systems).

2.4. Data processing

Consisted of: (a) R-wave peak, systolic pressure (SP) and diastolic pressure (DP) detection for the computation of the RR intervals (RRi), SP and DP time series; (b) cubic-spline interpolation, resampling at 4 Hz, and detrending of the time series with the smoothness priors method; (c) estimation of power spectra of RRi and SP series by the smoothed pseudo-Wigner-Ville distribution for computing the instantaneous power in absolute units of LF_{RR} and LF_{SP} components in the 0.04 to 0.15 Hz band, the HF_{RR} power in the 0.15 to 1.0 Hz band and the LF_{RR}/HF_{RR} ratio; (d) expressing the CVAV as changes from baseline, normalizing the force with respect to the MF achieved on each trial and constructing relationships between the %MF and CVAV for each subject and exercise type; (e) detecting the threshold phenomenon in the continuous functions, by selecting the inflection point with the V-slope method [9]; (f) ensemble averaging of the individual relationships, for visualization purposes only.

2.5. Statistical analysis

According to the Shapiro-Wilk test, data were normally distributed, except for the HF_{RR} power, to which a logarithmic transform was applied, and were expressed as mean ± sd. The linear regressions and correlation coefficients of all the individual relations were computed. Student's paired *t*-test was employed to compare the slopes and correlation coefficients between HG and LE. Statistical significance was accepted at $p<0.05$.

3. Results

In both LE (Fig. 1A) and HG (Fig. 1B) the contraction force continuously increased until fatigue showed very strong correlations with time. The MF achieved by HG and LE were not different ($p>0.05$). The error between the target linear intensity pattern and the force achieved by the subjects was greater for LE than HG.

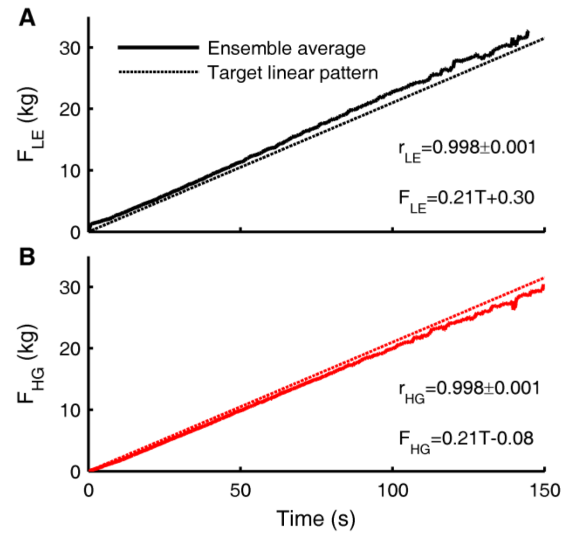

Figure 1. Time course of contraction force in both LE (A) and HG (B) with respect to the target linear pattern.

Figure 2 shows a representative example of TFD of RRi and SP series during LE.

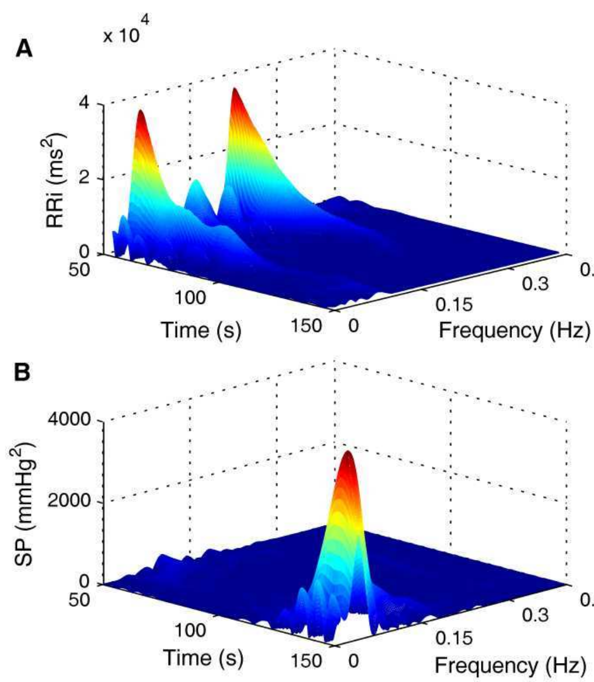

Figure 2. Typical examples of TFD of (A) RRi and (B) SP series during LE.

In the two IE types the %MF-RRi relationships presented strong correlations. The regressions slopes and correlations were greater ($p<0.001$) for LE (Fig. 3A). In both LE and HG, the inverse %MF-lnHF_{RR} relations showed strong linear correlations and an abrupt decrease around 90%MF (Fig. 3B, Table 1).

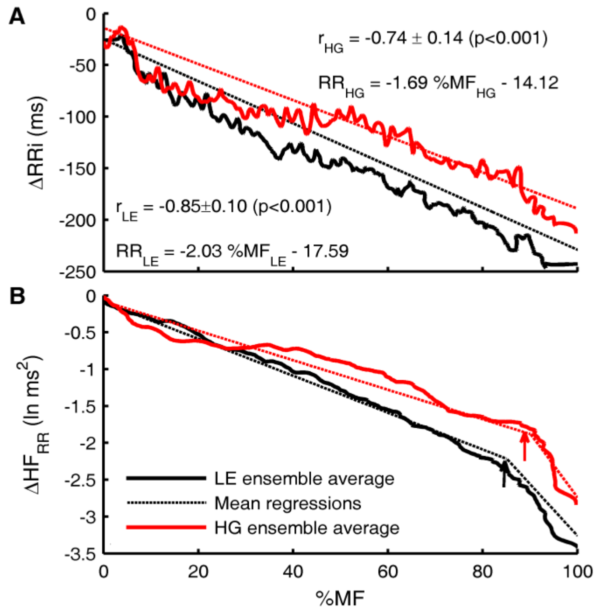

Figure 3. Continuous relations between %MF and CVAV.

Table 1. Correlation coefficients (r) and regression slopes (m) of the %MF-CVAV relations for both IE types before (BT) and after threshold (AT) force. Mean ± sd, N=35.

		BT		AT	
		LE	HG	LE	HG
SP	r	0.83±0.10†	0.52±0.23†	0.68±0.20†	0.67±0.16†
mmHg	m	0.36±0.15‡	0.19±0.13	0.88±0.39‡	0.39±0.24
DP	r	0.74±0.12†	0.43±0.23†	0.80±0.10†	0.75±0.12†
mmHg	m	0.27±0.08‡	0.12±0.07	0.59±0.28‡	0.47±0.22
$lnHF_{RR}$	r	-0.76±0.23†	-0.71±0.25†	-0.74±0.20†	-0.73±0.21†
ms^2	m	-0.02±0.01	-0.02±0.01	-0.06±0.05	-0.09±0.09
LF_{SP}	r	-0.22±0.59	-0.57±0.35†	0.84±0.10†	0.81±0.15†
$mmHg^2$	m	-0.14±0.31	-0.21±0.23	2.06±2.27‡	1.03±1.23
LF_{RR}	r	-0.01±0.55	-0.23±0.51	0.78±0.10†	0.70±0.19†
HF_{RR}	m	0.01±0.03	-0.02±0.04	0.45±0.46‡	0.18±0.21

† p<0.001; ‡ p<0.001 between LE and HG.

In both IE types the %MF-SP relations showed an inflection point near 65%MF (Fig. 4A). The %MF-DP relation presented higher ($p<0.01$) after threshold (AT) correlations than %MF-SP (Table 1).

The %MF-LF_{RR}/HF_{RR} relations showed a linear increase after 65%MF (Fig. 4C, Table 1), behavior also depicted by the %MF-LF_{SP} relations. These two relations presented weak correlations and below baseline levels in the before threshold stage (Table 1). The relations corresponding to LE presented steeper regression slopes ($p<0.001$) than those of HG, particularly in the AT stage (Table 1), except for the %MF-$lnHF_{RR}$ relations. The correlations between %MF and LF_{RR} were -0.15±0.47, $p>0.05$ and -0.14±0.54, $p>0.05$ for HG and LE, respectively. Tidal volume and respiratory frequency increased progressively during both types of IE.

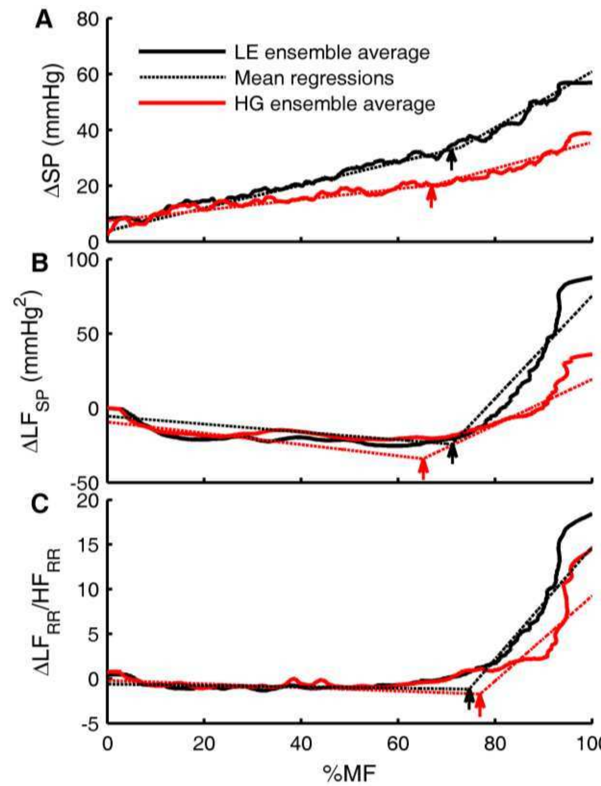

Figure 4. Threshold phenomena in the continuous %MF-CVAV relations, indicated by the inflection points (↑).

4. Discussion and conclusions

In this study we combined a protocol of continuously increased IE intensity with the spectral analysis of CVV performed by a TFD. This methodology allowed the construction of continuous relationships between the contraction force and CVAV in the widest range. In addition, since linear regressions are used, the comparisons between the responses produced by the two IE types were simpler. The relations found in the present study establish that: 1) RRi and vagal outflow responses are proportional to IE intensity in a wide range; 2) cardiac and vasomotor sympathetic estimators present intensity-dependent threshold phenomena; 3) the SP and DP responses are proportional to the intensity and show threshold phenomena; and 4) the effects of LE on CVAV are greater than those provoked by HG.

The few studies that have applied spectral analysis of CVV during IE [3,4,7] used a constant contraction intensity and spectral estimation methods that require stationary signals. In agreement with Takahashi et al. [6], we think that the cardiovascular series resulting from the administration of a single IE intensity sustained for several minutes would hardly be stationary, due to the progressively fatiguing nature of this type of effort. In general, authors do not test the stationarity of cardiovascular series. Therefore, TFD are the ideal tools to carry out the spectral analysis of CVV during IE.

The reported effects of IE on the CVV spectral measures are oversimplified, since they have been established using only one contraction intensity. For example, Iellamo et al. [7] reported, during static LE at 30%MVC, a decrease of the HF_{RR} power. In contrast, we could characterize the continuous variations of CVAV with respect to the IE intensity, from rest to fatigue.

Gálvez et al. [1], in two muscular groups at two IE intensities, found a non linear relationship between contraction intensity and HR. In our study, the degree of linear correlation between IE intensity and CVAV varied depending on the variable considered and the muscular group involved. While RRi and HF_{RR} vary in a predominantly linear fashion, LF_{RR}/HF_{RR} ratio and LF_{SP} power exhibit intensity-dependent threshold phenomena around 65%MF, with linear AT relations, and SP and DP present both characteristics.

The effect of IE on LF_{RR} power is unclear: while Iellamo et al. [7] documented its increase in both absolute and normalized units, Kiviniemi et al. [8] found no change in absolute units. In our study, this component showed no distinctive response pattern, probably because it reflects both sympathetic and vagal modulation [5].

The effect of IE intensity on LF_{SP} power has not been established. It has been reported that the LF_{SP} amplitude does not change during HG at 20%MVC [8]. By the findings of the present study, the dynamics of sympathovagal balance and LF_{SP} power during our IE protocol were similar, indicating the triggering of the metaboreflex. This mechanism is responsible of the AT sympathetic activity increase, as established by microneurography [10]. This agreement additionally supports the ability of the LF_{SP} to indicate vasomotor sympathetic outflow.

The findings of the present study support the interplay of vagal, cardiac and vasomotor sympathetic outflows in the control of HR and AP depending on IE intensity. Up to 90%MF, the HR increase is proportional to the vagal withdrawal. Around 65%MF the increase of the cardiac sympathetic outflow is added. Up to 65%MF, the main contributing factor to the AP rise is the HR increase, but afterwards the increase of both cardiac and vasomotor sympathetic outflows by the activation of the metaboreflex also contribute.

The greater effects produced by LE on all CVAV suggest that the degree of autonomic-muscular coactivation driven by central command depends on the muscular group involved.

In conclusion, combining a continuously increased until exhaustion IE protocol performed by two muscular groups with a TFD allows to characterize the effect of IE intensity and muscle group on CVAV, expressed as continuous relationships: while RRi and HF_{RR} responses are linear and inverse, LF_{SP} and LF_{RR}/HF_{RR} ratio show threshold phenomena, SP and DP are proportional and present threshold phenomena, being the responses to LE greater than HG.

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