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Biomechanics of the Ergometric Stress Tests: regional and local effects on elastic, transitional and muscular human arteries

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***Abstract*— Ergometric exercise stress tests (EST) give important information about the cardiovascular (CV) response to increased demands. The expected EST-related changes in variables like blood pressure and heart rate are known, but those in the arterial biomechanics are controversial and incompletely characterized. Aims: a) to characterize the *regional* and *local* arterial biomechanical behavior in response to EST, and its temporal profile in the post-EST recovery phase and (b) to compare different arteries biomechanical response to EST. Methods: In 16 non-trained healthy young subjects the carotid-femoral pulse wave velocity and the carotid, femoral and brachial arterial distensibility were non-invasively evaluated before (Rest) and after EST. Post exercise recordings were obtained 0-1, 4-5, and 9-10 minutes after exercise. Results: The EST resulted in an early increase in the arterial stiffness, evidenced by regional and local parameters. There were quali-quantitative differences among the arterial local stiffness response to EST, when analyzing conjunctly the different post-EST recovery stages. The biomechanical changes could not be explained only by blood pressure variations.**

I. Introduction

It is known that when evaluating the cardiovascular (CV) system studies performed at rest and during conditions of increased requirements (i.e. Ergometric exercise Stress Tests, EST) give complementary information. Taking into account this, the expected changes and temporal profiles of variables such as heart rate and blood pressure (BP) in response to EST have been characterized and are widely used in the clinical practice to evaluate the functional capability, in CV diagnosis and patients follow up. On the other hand, the arterial biomechanics role in the CV physiology and disease development has been recognized. Then, recent international guidelines [1] include the study of basal vascular biomechanics in the CV risk stratification, diagnostic, prognostic and follow up. However, it is noteworthy that subjects with normal basal vascular biomechanics could have an abnormal response to increases in CV demands. This has been frequently overlooked, and in our knowledge only few studies evaluated the vascular biomechanics during the exercise. Furthermore, the studies results are controversial.

The biomechanical response to exercise could differ, depending on the exercise developed and the vascular region analyzed, taking into account the structural and functional differences among arteries (i.e. elastic, like the carotid vs. muscular, like the femoral) [2], [3]. Hence, an adequate characterization of the vascular response to a particular EST requires evaluating regional parameters, and a simultaneous analysis of different arterial segments local response.

In this context, the aims of this work, developed in healthy non-trained young subjects, were: a) to characterize regional (carotid-femoral) and local changes in elastic, muscular and transitional arteries biomechanics in response to EST, b) to determine the temporal profile of the vascular biomechanics changes during the post-exercise recovery phase, and c) to compare the biomechanical response to exercise among different arterial segments. In addition, taking into account the BP-dependence of the biomechanical properties, the relationship between the BP and local biomechanical changes was analyzed. Hence, isobaric analyses were done.

II. Methods

A. Subjects

Sixteen healthy, non-trained, active adults (11 women), without CV risk factors and free of CV or other chronic diseases were studied. None of the subjects was taking CV

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acting medications. The Human Research Committee of the Republic University (Uruguay) approved all procedures. All subjects gave written informed consent. The study was carried out according to international ethic rules and the Helsinki Declaration principles. The subjects' main characteristics are detailed in Table I.

TABLE I
GROUP CHARACTERISTICS

Age [Years]	21 ± 1
Body weight [Kg.]	63 ± 8
Body height [m]	1.65 ± 0.15
BMI [Kg/m^2]	22.09 ± 2.0
Hip perimeter [cm]	94.38 ± 7.47
Waist perimeter [cm]	73.33 ± 5.64

Values expressed as mean ± standard deviation

B. *Experimental protocol*

In each experimental session, brachial BP, electrocardiogram and *regional* (left carotid-femoral pulse wave velocity, PWV) and *local* (distensibility) arterial stiffness measurements were obtained before (Rest) and after bicycle EST. Post exercise recordings were obtained 0-1 (PE1), 4-5 (PE2) and 9-10 (PE3) minutes after exercise. All measurements were done with the subject in supine position in a controlled environment at 22°C [1].

C. *Arterial non-invasive studies: regional and local biomechanics*

Arterial non-invasive studies were done according to international consensus [1]. To evaluate the aorto-iliac *regional* biomechanical behavior, the carotid-femoral PWV was measured using strain gauge mechano-transducers (Motorola MPX 2050, Motorola Inc., Corporate 1303 E. Algonquin Road, Schaumburg, Illinois 60196, USA) placed simultaneously on the skin over the carotid and femoral arteries [4]. Signals were recorded and digitized for off-line analysis. Given the distance between the sensors, the PWV was calculated for 10 consecutive pulses, and the average was used for further analysis. All measurements were made by the same operator, avoiding inter-operator differences. The PWV variation coefficient was less than 5%.

The carotid, brachial and femoral arteries *local* distensibility was characterized through the analysis of the systo-diastolic diameter-pressure relationship. To evaluate the diameter each artery was visualized longitudinally by high resolution B-Mode ultrasound (Sampling rate: 30 Hz; 7.5-MHz probe; Portable Ultrasound System, Model: Aloka SSD210, ALOKA CO., LTD. Tokyo, Japan) [4]. Video sequences (10-15s) were recorded and analyzed off-line by a reader using an automated step-by-step algorithm applied to each digitalized image [5]. Since, peripheral and central arterial pressure can differ, the carotid and femoral systolic and diastolic pressure values were calculated by means of the diameter waveform calibration [6], [7]. To accomplish this approach, diameter waveforms were calibrated using an exponential calibration scheme, applying Vermeersch et al. [6] method, modified from that of Meinders and Hoeks [7]. The method assumes an exponential relationship between pressure and diameter: $p(t) = p_d \exp\left[\alpha\left(\frac{A(t)}{Ad} - 1\right)\right]$ (Eq. 1), with $A(t) = \frac{\pi d^2(t)}{4}$ (Eq. 2) $\alpha = \frac{Ad\ In\ (\frac{Ps}{Pd})}{As - Ad}$ (Eq. 3), where p(t) is the BP waveform, d(t) is the diameter waveform, A(t) is the arterial cross-section as a function of time, Pd and Ps are end diastolic and systolic pressure levels, respectively; Ad and As are end diastolic and systolic arterial cross-section areas, respectively, and α is the pressure-independent wall stiffness coefficient [6], [7]. To use equation (1) to calculate the pressure waveform from a given diameter waveform, systolic and diastolic pressures, and the arterial cross-section must be known at the same site. Mean and diastolic arterial pressure can be assumed to remain constant throughout large arteries [1], [2], [6], [7], furthermore in supine position. Then, the iterative scheme can be used to determine α based in mean and diastolic brachial pressures [6], [7]. To this end, according with Meinders et al. [7] mean arterial BP was calculated from brachial recordings as: bMBP = bDBP + (bSBP − bDBP)/3, where bMBP, bDBP and bSBP, are mean, diastolic and systolic brachial pressures, respectively. After obtaining the carotid and femoral pressure waveforms, derived from the diameter waveform using the exponential model, systolic and diastolic femoral (fSBP and fDBP) and carotid (cSBP and cDBP) pressure values were obtained. After that, we calculated the effective arterial distensibility (AD_E), a parameter commonly used in the clinical practice, since it can be obtained just using systolic (maximal) and diastolic (minimal) pressure and diameter values [1]. The AD_E was calculated as: $AD_E = \frac{SD - DD}{SBP - DBP} DD$ (Eq. 4), SD and DD are the systolic and diastolic internal diameters, respectively.

To discriminate potential pressure-dependent and pressure-independent (i.e. smooth muscle tone-related changes) effects on the arterial biomechanics, associated with the EST, the "passive isobaric" arterial distensibility (AD_{PI}) was calculated for the pressure levels observed after the EST. To this end, the pressure-diameter logarithmic relationship was

obtained at rest and the AD_{PI} quantified for the pressure levels observed in response to the exercise. In other words, AD_{PI} was calculated using the rest systo-diastolic diameter variations, corresponding to the systo-diastolic variations in pressure obtained post-exercise. Then, AD_{PI} represents the distensibility expected at rest, if pressure levels were those observed in PE1, PE2 and PE3. The AD_{PI} and AD_E comparison allowed evaluating if the arterial distensibility variations could be explained by the pressure changes. This approach has been used previously [8].

D. Statistics

Changes in pressure, heart rate (HR), PWV, AD_E, AD_{PI}, and arterial diameter, associated with the EST were evaluated using ANOVA + Bonferroni test. Differences between AD_E and AD_{PI} were evaluated using two tailed paired Student t-test. A $P<0.05$ indicated significant statistical differences.

III. Results

The Figure 1 shows brachial BP (Top), HR (Middle), and mean arterial diameter (Bottom) levels obtained at rest and at different stages in the EST recovery phase. Note that PE1 showed statistical differences in systolic and diastolic pressure levels with respect to rest, PE2 and PE3 states. However, as was expected, as a result of the systolic (increase) and diastolic (decrease) changes in pressure, the mean BP kept unchanged after the EST.

The Figure 2 shows AD_E and AD_{PI} for the elastic (carotid), muscular (femoral) and transitional (brachial) arteries at rest and after EST.

The Figure 3 shows PWV levels at rest and after EST.

IV. Discussion

In this work, for the first time, the temporal profile of EST-related changes in regional and local biomechanics of elastic, transitional and muscular arteries from healthy young subjects was characterized. The main results were:

a) The EST resulted in an early (PE1), generalized increase in the arterial stiffness, evidenced by both, regional and local parameters [Figures 2 and 3].

b) When analyzing all the post-EST recovery stages (PE1-PE3) studied, there were quali-quantitative differences among the arterial stiffness response to exercise [Figure 2].

c) The arterial biomechanical changes associated with the exercise could not be explained only by blood pressure variations.

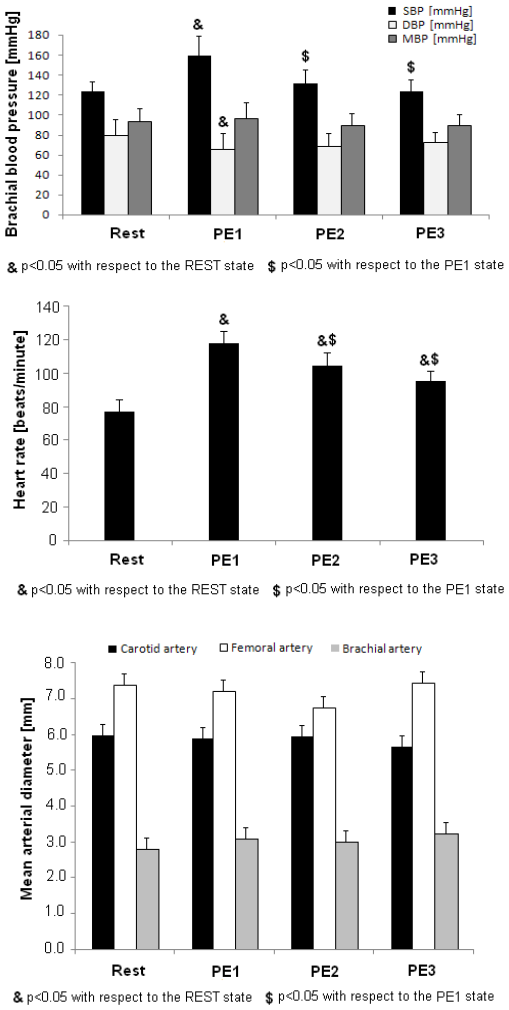

Fig. 1. Brachial pressure (Top), heart rate (Middle) and arterial diameter (Bottom), obtained at rest and after exercise (PE1-PE3).

All the arterial types increased the stiffness immediately after the EST [Figure 2], but there were quantitative differences in the changes among the vascular segments. The increase was 14%, 43% and 57% in the femoral, carotid and brachial arteries, respectively. In addition, considering PE2 and PE3 there were quantitative, but also qualitative differences in the biomechanical response and its temporal profile among the arteries [Figure 2]. While the femoral distensibility increased, reaching values higher than those of rest, the carotid distensibility achieved rapidly rest levels and the brachial distensibility did not reach rest levels in the recovery time analyzed. The dissimilar response could be explained, at least partially, by structural/functional vascular differences and/or by different haemodynamic, EST-related changes in the studied territories that could result in a

different capability to respond to exercise, (i.e. muscular arteries –femoral- could concentrate the ability to minimize left ventricle afterload and to ensure an adequate lower-limb perfusion during EST).

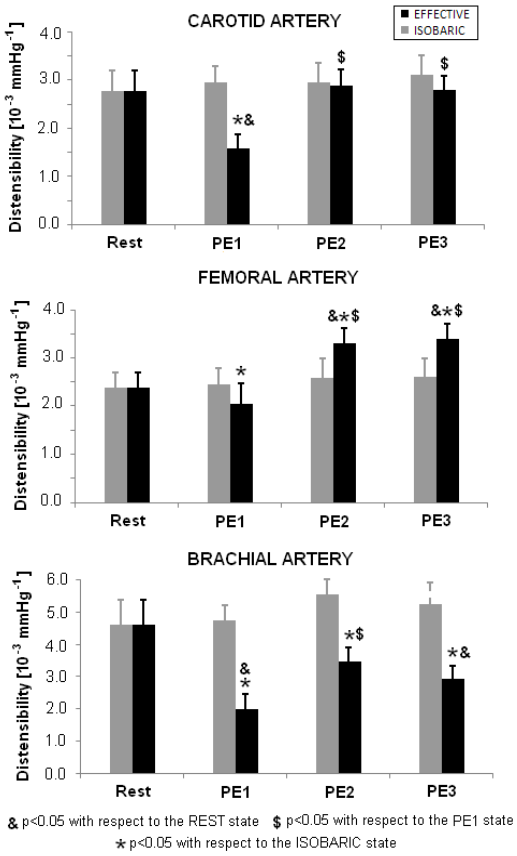

Fig. 2. Carotid (top), femoral (middle) and brachial (bottom) effective and passive isobaric distensibility, obtained at rest and after exercise (PE1-PE3)

As it is known arterial stiffness depends on the arterial pressure, and the exercise is associated with pressure changes (i.e. systolic BP increase and diastolic BP reduction due to, respectively, the stroke volume increase and the peripheral dilatation) [2]. To evaluate the stiffness changes pressure-dependence AD_E and AD_{PI} were calculated.

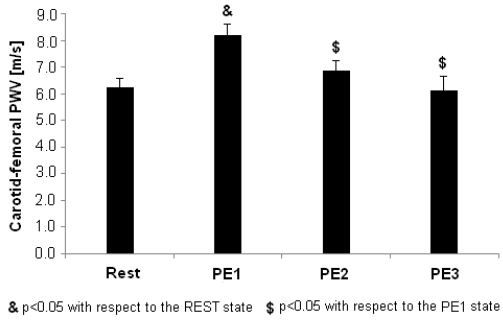

Fig. 3. Carotid-femoral PWV at rest and after exercise (PE1-PE3).

The AD_E and the values expected only due to the pressure levels (AD_{PI}) differed [Figure 2]. The differences were qualitative and quantitative, and varied depending on the segment considered. Hence, the biomechanical changes could not be ascribed to the BP variations. Instead, pressure-independent, like smooth muscle tone-dependent mechanisms could contribute to explain the distensibility variations found in post-exercise recovery phase.

V. Conclusion

EST resulted in regional and local arterial stiffness changes. The study of the vascular biomechanics response to EST could add to the CV risk stratification and/or diagnostic. Further works are necessary to characterize the vascular biomechanics response to EST in different populations and to define its clinical meaning and applicability.

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