Biomechanics of Ergometric Stress Test: 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. In this context, this work aims were to characterize the regional and local arterial biomechanical behaviour in response to EST; to evaluate its temporal profile in the post-EST recovery phase; and to compare the biomechanical response of different 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. Main results: The EST resulted in an early increase in the arterial stiffness, evidenced by both, regional and local parameters (pulse wave velocity increase and distensibility reduction). When analyzing conjunctly the different post-EST recovery stages there were quali-quantitative differences among the arterial local stiffness response to EST. The biomechanical changes could not be explained only by blood pressure variations.

1. 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 test, EST) give complementary information. The expected changes and temporal profiles of variables like heart rate and blood pressure (BP) in response to EST have been characterized, and altered responses of such variables have shown to be associated with CV risk and/or prognostic. Then, the evaluation of changes in HR and arterial pressure in response to EST is widely used in clinical practice in the evaluation of functional capability, in CV diagnosis and patients follow up. On the other hand, it is recognized the role of the arterial biomechanics in the CV physiology and disease development.

Taking into account this, recent international guidelines [1] included 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 increased 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.

Taking into account the structural and functional differences among arteries and their different role in the cardiovascular system, the biomechanical response to exercise could differ, depending on the exercise developed, as well as on the vascular region and vessels analyzed (i.e. elastic arteries, like the carotid vs. muscular arteries 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 arteries local response.

Several approaches are used to evaluate, non-invasively, the arterial system biomechanical behaviour. Among them, the analysis of the pressure-diameter relationship in a given arterial segment is considered the gold standard in ‘local’ stiffness evaluation, while the pulse wave velocity measurement is accepted as the gold standard for assessing ‘regional’ stiffness [1].

In this context, this work aims were: a) to characterize regional (carotid-femoral) and local (elastic, muscular and transitional arteries) changes in vascular stiffness 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, and d) to analyze the relationship between the biomechanical changes and BP, taking into account the pressure dependence of the arterial stiffness (isobaric analysis). In other words, the work general aim was to determine the arterial stiffness changes associated to the EST using complementary approaches and gold standard parameters.

2. Materials and methods

2.1 Subjects
Sixteen healthy, non-trained, active adults (11 women), without CV risk factors and free of CV and other chronic diseases were studied. None of the subjects was taking CV acting medications. The study was carried out according to international ethic rules and the Helsinki Declaration principles. All procedures were approved by the Republic University (Uruguay) Human Research Committee. Subjects gave written informed consent. The subjects’ main characteristics are detailed in the Table.

| Table. Subjects main characteristics. |
|--------------------------------------|
| Age [Years] | 21 ± 1 |
| Body weight [Kg.] | 63 ± 8 |
| Body height [m] | 1.65 ± 0.15 |
| BMI [Kg/m²] | 22.1 ± 2.0 |
| Hip perimeter [cm] | 94.38 ± 7.47 |
| Waist perimeter [cm] | 73.33 ± 5.64 |

Values expressed as mean ± standard deviation

2.2 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 the exercise. All measurements were done with the subject in supine position, in a quite room, with controlled-temperature (22°C) [1].
2.3 Arterial non-invasive studies: pulse wave velocity and arterial distensibility
Arterial non-invasive studies were done according to international consensus [1]. To evaluate the aorto-iliac regional biomechanical behaviour, the carotid-femoral PWV was measured using strain gauge mechno-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 ($\Delta x$) between the mechno-transducers, the PWV was calculated for 10 consecutive pulses as $\text{PWV}=\Delta x/\Delta t$, where $\Delta t$ is the time difference between the maximum upstroke $dP/dt$ of the carotid and femoral waves (Figure 1). The average PWV was used for further analysis. All measurements were made by the same operator. PWV variation coefficient was less than 5%.

The carotid, brachial and femoral 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) and video sequences (10-15s) were recorded [4]. Then, the recorded sequences were analyzed off-line using an automated step-by-step algorithm applied to each digitalized image that allowed obtaining the diameter signal [5].

To determine the carotid and femoral peak systolic (SBP) and minimum diastolic (DBP) pressure levels, taking into account that pulse pressure (PP) may differ between central and peripheral arteries, the carotid and femoral pressure waves were calibrated using brachial pressure values obtained by sphygmomanometry [1]. To do this, since DBP and mean pressure (MBP: $\text{MBP}=\text{DBP}+(\text{SBP}-\text{DBP})/3$) do not vary along the arterial system (especially in supine position) the DBP and MBP values measured in the brachial artery were assigned, respectively, to the minimum and average values of the carotid and femoral pressure waves. Then, the carotid and femoral SBP and PP levels were obtained [1] [2].

Subsequently, the effective arterial compliance (ADE), a parameter commonly used in clinical practice, was calculated: $\text{ADE}=(\text{SD-DD})/(\text{SBP-DBP})/\text{DD}$, where SD and DD are the systolic and diastolic internal diameters, respectively.

Finally, in order to discriminate potential pressure-dependent and pressure-independent (i.e. smooth muscle tone-related) biomechanical changes associated with EST, the passive isobaric arterial distensibility (ADPI) was calculated for the pressure levels observed after EST. To this end, the pressure-diameter logarithmic relationship was obtained at rest and the ADPI quantified for the pressure levels observed in response to the exercise. Then, ADPI would represent the distensibility expected at rest, if pressure levels were those observed in PE1, PE2 and PE3. The ADPI and ADE comparison allowed evaluating if the arterial distensibility variations could be explained by the pressure changes [6].
2.4 Statistics
Data are shown as mean value +/- standard deviation.

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

3. Results
Figure 2 shows brachial BP (top), HR (middle) and mean arterial diameter (bottom) levels, obtained at rest and at different stages in the EST recovery phase (PE1, PE2 and PE3). Note that PE1 showed differences in both, systolic and diastolic pressure levels, with respect to rest conditions, PE2 and PE3 stages. However, as was expected, as a result of the systolic (increase) and diastolic (decrease) changes in pressure, MBP kept unchanged after the EST.
Figure 2: Brachial pressure (Top), heart rate (Middle) and arterial diameter (Bottom), obtained at rest and after exercise (PE1-PE3).

Figure 3 shows ADE and ADPI for the elastic (carotid), muscular (femoral) and transitional (brachial) arteries, at rest, and after EST. It is noteworthy, that in all the studied arteries, EST resulted in an early decrease in DAE, with quantitative differences among the vascular segments studied. Furthermore, after PE1, DAE changes varied, depending on the analyzed artery: in the femoral, DAE increased, reaching levels higher than those found at rest; in the carotid, DAE returned to basal values and it kept in low levels in the brachial artery.
The PWV basal and post-EST levels are shown in figure 4. Note that EST resulted in an early increase in PWV (higher aorto-iliac arterial stiffness), followed by basal levels recovery.
4. Discussion

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

1. The EST resulted in an early (PE1), generalized increase in the arterial stiffness evidenced by both, regional (PWV) and local (distensibility) parameters (Figure 3 and 4).
2. All post-EST recovery stages studied (PE1-PE3) showed quali-quantitative differences in local arterial stiffness (Figure 3).
3. The local arterial biomechanical changes associated with the exercise could not be explained only by blood pressure variations (Figure 3).

Although all the arterial types increased its stiffness immediately after the EST [Figure 2], the changes among the vascular segments were quantitatively different. 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 3).

While the femoral distensibility increased, reaching values higher than those of rest, the carotid distensibility achieved rapidly rest levels and 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 increased conditions of metabolic demands).

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, the stroke volume increase and the peripheral dilatation respectively) [2].

To evaluate the pressure-dependence of the stiffness changes associated with EST, the ADE and ADPI were compared. There were differences between both parameters, being the differences highly dependent on the post-EST stage and the vascular segment studied. Looking at these results, the DAE changes could not be ascribed only to BP variations. Instead, pressure-independent, like smooth muscle tone-dependent mechanisms could contribute to explain the distensibility variations found in the post-exercise recovery phase.
5. Conclusion

The EST resulted in regional and local arterial stiffness changes. Local changes were highly dependent on the vascular segment considered. The study of the vascular biomechanics response to EST could add to the CV risk stratification, diagnostic and/or prognostic. About this, further works are necessary to characterize the vascular biomechanical response to EST in different populations and to define its clinical meaning and applicability.

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6. References

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