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Stroke Work Damping Ratio is Increased in Trained Athletes*

L. Lemes Coitinho, L. J. Cymberknop, *Senior Member*, *IEEE*, I. Farro, F. Martinez, C. Américo, N. Lluberas, G. Parma, J. Aramburu and R. L. Armentano, *Senior Member, IEEE*

Abstract— **INTRODUCTION: Athletes training is often associated with morphological changes in the heart. In this sense, the ventricular pressure-volume (PV) relation provides a complete characterization of cardiac pump performance. Regarding the arterial system (AS), arterial wall viscosity is a source of energy dissipation, that takes place during mechanical transduction. Left ventricular stroke work (SW) constitutes the useful fraction of ventricular energy that is delivered to the AS. OBJECTIVE: Left ventricular PV-loops were evaluated in terms of AS viscous property, by means of the interaction of two SW components (Stroke Work Damping Ratio, SWDR), both in untrained and trained subjects. MATERIAL AND METHODS: Fourteen healthy individuals (seven trained) were noninvasively evaluated in terms of echocardiographic and aortic pressure measurements. RESULTS: SWDR was observed to be increased in trained subjects. CONCLUSION: SWDR was evaluated in trained individuals, being increased in comparison with the non-trained group. This effect is a consequence of a significant increase of SWD, which could be related with the viscous mechanical property of AS.**

I. Introduction

The cardiovascular (CV) system produces a complex response to exercise, that induces modifications in the functions of the different target organs. Carrying out physical activity involves an increase in the oxygen and nutrient demands of the exercised muscles, which makes the CV system to increase the blood supply (the cardiac output) to meet these needs. As a result, morphological alterations in the heart, including increments in left ventricular (LV) chamber size, wall thickness and mass are usually related with athletes training. Left ventricular hypertrophy is generally present, characterized by an unaffected relationship between left ventricular wall thickness and left ventricular radius [1].

The LV pressure-volume (PV) relation provides a complete characterization of cardiac pump functioning. A 'PV-loop', can be constructed by the combination of the simultaneous measurements of the intraventricular pressure and volume, which can be obtained during several comparable cardiac beats [2]. Principally, the PV-loop analysis can elucidate pathophysiological mechanisms of heart failure, myocardial and valvular heart diseases, as well as monitoring the effects of therapeutic interventions [3]. On the other hand, the arterial system (AS) can be described as a chamber that stores blood, which is provided by left ventricle. During the systolic phase, blood volume is pumped into the large arteries, which expand as a result of increasing pressure. Subsequently the vessels recoil (during diastole), propelling the blood through the capillaries. From this point of view, an AS PV-loop can also be defined [4]. The area delimited by a LV PV-loop is defined as the stroke work (SW) produced during a cardiac cycle. SW constitutes the useful fraction of ventricular energy that is supplied to AS (through the aorta), in order to forward blood flow and guarantee an adequate transport of oxygen [2]. It is well known that, during the ejection period, the LV PV-loop behavior is affected by arterial load, due to the aortic valve is opened. Outside the cardiac muscle, the AS PV-loop is related to intrinsic mechanical properties such as vessel compliance, as well as extrinsic properties such as ventricular contractility. Additionally, AS PV loops travel clockwise (while LV PV-loops evolution is in the opposite direction), indicating that energy is being dissipated [4].

Arterial wall viscosity (AWV) is a source of energy dissipation, that takes place during mechanical transduction. Whereas part of the energy stored during elastic distension of the vessel is fully restored, the remaining part of the energy corresponding mainly to the viscous deformation is dissipated within the arterial wall. This characteristic exhibited by the AS PV-loop can be quantified throughout its hysteresis area, which is mainly a consequence of the presence of vascular smooth muscle (VSM) cells in the arterial media layer. [5]. Particularly, the AS PV 'pure elastic relationship' is evidenced during the diastolic phase. Considering then that LV is fully coupled to aorta, the AS PV-loop can be 'inversely reflected' to the LV PV-loop and analyzed as a constitutive part of the loop area. Accordingly, SW was considered to be represented by two main components: SW_V, which is related to the AS viscous behavior and SW_E, related to the elastic behavior. Thus, the concept of 'damping' (the dissipation of the energy stored in an oscillation phenomenon) was fully applied to the LV PV-loop evaluation.

Previous studies have shown that arterial wall viscous property is increased in endurance-trained men [6]. In this work, noninvasively obtained LV PV-loops were evaluated in terms of SW components in untrained and trained subjects. Although changes in hemodynamic parameters such as ventricular elastances, arterial-ventricular coupling (AVC), total arterial compliance (TAC) and systemic vascular resistance (SVR) that occur in trained subjects are already known, the contribution of the AS viscous component to exercise dynamics in terms of SW remains unclear. As a result, a novel measure is proposed in this work to evaluate the

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L. Lemes, I. Farro and R. L. Armentano are with Departamento de Ingeniería Biológica, Facultad de Ingeniería, Universidad de la República, Montevideo, Uruguay

L. J. Cymberknop and R. L. Armentano are with Universidad Tecnológica Nacional, Buenos Aires, Argentina (e-mail: ljcymber@ieee.org)

I. Farro, F. Martinez, C. Américo, N. Lluberas, G. Parma and J. Aramburu are with Cardiovascular Images Department, Cardiocentro, Asociación Española of Montevideo, Uruguay

interaction between LV and AS, defined as 'Stroke Work Damping Ratio' (SWDR).

II. Materials an Methods

A. Study Population

Fourteen healthy individuals, free of known cardiovascular disease, were evaluated at Echocardiography Lab at Cardiocentro, Asociación Española of Montevideo, Uruguay, in terms of their clinical, echocardiographic and hemodynamic features. Firstly, seven participants with no practice of athletic exercise and aged between 21 and 39 years old, were included in this study as the untrained group (UG). Subsequently, seven participants referred to the service for competitive assessment (soccer players, a combination of endurance and strength training), were included as the trained group (TG). Height and weight were measured, and body mass index (BMI) and body surface area (BSA) were calculated. Systolic and diastolic blood pressure measurements (SBP and DBP, respectively) were performed using a sphygmomanometer, in accordance to the Guidelines of the European Society of Hypertension. This study was approved by an independent institutional review board and all participants provided written informed consent.

B. Echocardiographic Protocol and Data Acquisition

All echocardiographic studies were performed by the same cardiologist and supervised during the entire study. Two-dimensional echocardiography (Vivid S70 ultrasound system; GE Medical Milwaukee, Wisconsin, USA; with a 3.0 MHz transducer) in combination with 12-lead electrocardiographic (ECG) monitoring were performed in all individuals. Systolic and diastolic brachial blood pressure values (SBD and DBP, respectively) jointly with ECG recordings were obtained in each stage of the test. The echocardiographic images were acquired in the parasternal long-axis, short-axis, and apical four, two, three and five chambers in baseline stage. Left ventricular end-diastolic and end-systolic volumes (ESV and EDV, respectively) were evaluated by automatic estimation of the subendocardial border in 4 and 2 chambers, using EchoPac version 203 GE HealthCare software, for left ventricular ejection fraction (LVEF) calculation (auto LVEF) using the biplane Simpson method. The frame with the smallest left ventricular cavity was considered to be the end-systolic frame [7]. ESV and EDV were then corrected by BSA (ESVI and EDVI, respectively). Similarly, indexed cardiac output (cardiac index, CI) was calculated in terms of the product between stroke volume (SV=ESVI-EDVI) and heart rate (HR).

Pulse wave analysis (PWA) was used to obtain the ascending aortic pressure waveform (AP) using a brachial cuff-based oscillometric device (SphygmoCor® XCEL, AtCor Medical, Sydney, Australia). Brachial pressure waveforms are obtained using a brachial oscillometric cuff and reconstruction of central aortic pressure waveforms is carried out in terms of a generalized transfer function (GTF) after calibration of cuff-derived brachial SBP and DBP [8]. All measurements were performed with the subject in supine position. Both AP assessment and echocardiographic evaluations were simultaneously performed using an ECG-gated system.

C. Left Ventricular Function Parameters

In order to characterizes the interplay between the heart and arterial system, AVC was calculated, as the ratio between arterial elastance (E_A) and end systolic left ventricular elastance (E_{LV}). E_A quantifies the workload imposed on the ventricle by the arteries (a measure of afterload) while E_{LV} constitutes a load-independent measure of cardiac performance. As a result, the coupling ratio describes how LV vs afterload interaction is able to modify cardiovascular reserve, cardiac performance and peripheral hemodynamics. Exercise in healthy individuals elevates E_{LV} but reduces Ea lowering E_A/E_{LV}, and suggesting more efficient energy transfer from the LV to the periphery (SW) [9], [3]:

$$E_A = \frac{ESP - EDP}{SV};\ E_{LV} = \frac{ESP}{ESV - V_0};\ AVC = \frac{E_A}{E_{LV}}, \quad (1)$$

where SV is the stroke volume (EDV-ESV), ESP is the end systolic pressure (which was determined in terms of the minimal ventricular volume occurrence obtained from instantaneous volume variations and EDP is the end diastolic pressure. V_0 is the theoretical volume when no ventricular pressure is generated, which was assumed (in this study) to be negligible compared with ESV. Pulse pressure (PP=SBP-DBP) and SV were used to determine TAC and SVR, both in UG and TG [10]:

$$TAC = \frac{SV}{PP};\ SVR = \frac{MAP}{SV \cdot HR}, \quad (2)$$

where MAP is the mean arterial pressure which was calculated as (2 ∗ diastolic blood pressure + systolic blood pressure)/3 and SVR was corrected by cardiac cycle T (SVR/T) [OTSUKI]. Finally, CV variables were normalized to body size, depicted by the suffix "I" (e.g., E_AI and E_{LV}I).

D. Pressure-Volumes Loops Analysis

Ideally, the PV loop can be rectangular or trapezoidal, where the four phases of the cardiac cycle are described: isovolumetric contraction, ejection, isovolumetric relaxation, and passive filling [3]. In this study, single LV PV-Loops were constructed based on the obtained noninvasive measurements. Firstly, ventricular pressure was estimated by means of instantaneous AP variations during the ejection period (measured AP morphology). Instantaneous ventricular volume variations were obtained from the echocardiographic images, (frame by frame analysis), averaging the volumes obtained automatically in 4 and 2 cameras. Finally, EDP was derived from Eq. 1, where E_A was estimated by means of SVR and AC values [11]. EDP was considered to be a constant value during the cardiac filling period and isovolumic contraction and relaxation were considered to behave ideally (Fig. 1). Ventricular pressure and volume time series were then processed for the generation and evaluation of the 'estimated PV loop' by means of an algorithm developed on Matlab® platform (Mathworks INC., Massachusetts, USA).

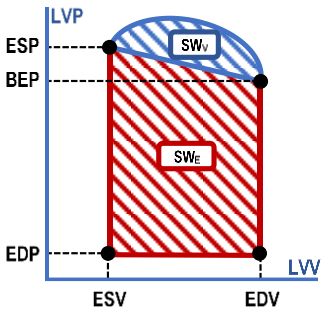

Fig. 1 – Noninvasively estimated Left Ventricular PV-Loop. ESP: End Systolic Pressure, EDP: End diastolyc pressure. BEP: Beginning of ejection pressure. ESV: End systolic volume, EDV: End diastolic Volume. LVP: Left ventricular pressure, LVV: Left Ventricular Volume. SW_V: Viscous Stroke Work, SW_E: Elastic stroke work

SW is the useful fraction of ventricular energy generated by the ventricle that is lost as blood flows through the circulation and it is used to beat the vascular load [2], [9]. In this study, SW (measured in terms of the PV-loop delimited area) was considered as the sum of two different components:

$$SW = SW_E + SW_V, \quad (3)$$

where SW_V (the viscous component) is circumscribed by the counterclockwise evolution of the PV loop delimited by the ejection phase (from EDV; BEP to ESV; ESP) and the return to ESV; ESP though a pure elastic relationship, which was assumed to vary linearly. On the other hand, SW_E constitutes the remaining portion of PV-loop enclosed area (defined as the 'elastic' component of SW, Fig. 1). As damping refers to the extraction of mechanical energy from a vibrating system usually by conversion of this energy into heat a result, the SWDR was be defined as:

$$SWDR = \frac{SW_V}{SW_E}. \quad (4)$$

Basically, SWDR represents fraction of SW_E, which is related to the elastic energy delivered to AS. The amount of energy dissipated constitutes a measure of a damping level [5].

E. Statistical Analysis

Continuous variables were expressed as mean ± SD. Independent sample Student's t-test was used to compare the mean values of different groups. Statistical significance was assigned to $P < 0.05$.

III. Results

Table I describes the demographic and clinical of both groups. Significant differences were found in age, BMI and blood pressure values but not in weight, height and HR ($p<0.05$). Echocardiographic characteristics are summarized in Table II. Both ESV and EDV were higher in trained individuals ($p<0.05$). As was expected, CI and LVEF were also significantly higher in TG with respect to UG. In table III, obtained hemodynamic parameters are shown. Firstly, SVR was significantly lower in TG while AC was significantly higher ($p<0.05$). Both ventricular elastances ($E_{LV}I$ and E_AI) showed a significant decrease in TG with respect to UG whereas the same behavior was observed in AVC. Regarding SW values, SWI and SW_VI were significantly greater in TG, giving rise to a markedly increase of SWDR (damping effect) in trained individuals ($p<0.05$). On the other hand, non-significant differences were found in SW_EI.

TABLE I. Demographics and Clinical Characteristics. Values are expressed as mean±standard deviation. BMI: Body Mass Index (kg/m^2), SBP: Systolic Blood Pressure, DBP: Diastolic Blood Pressure (sufix b: Brachial, sufix a: Aortic), HR: Heart Rate [bpm]. *P<0.05 was considered as statistically signficant

Demographic and Clinical Data		
Parameter	***Untrained Group***	***Trained Group***
#	7	7
Age [years]	31.6±6.6	19.0±10.6*
Height [cm]	173.4±6.8	172.4±11.0
Weight [kg]	75.4±6.7	68.4±9.6
BMI [kg/m^2]	25.1±1.7	22.9±0.8*
SBPb [mmHg]	131.6±17.4	113.3±14.2*
DBPb [mmHg]	86.7±9.2	64.1±10.2*
SBPa [mmHg]	118.4±14.4	98.5±11.9*
DBPa [mmHg]	87.2±10.2	64.0±10.3*
HR [bpm]	75.1±15.0	62.3±13.1

TABLE II. Echocardiographic Characteristics Corresponding to both grups. ESVI: End Systolic Volume, EDVI: End Diastolic Volume. Both volumes were Indexed by body surface area (BSA). CI: Cardiac Index (cardiac output indexed by BSA), LVEF: Left Ventricular Ejection Fraction [%]. *P<0.05 was considered as statistically signficant

Echocardiographic Data		
Parameter	***Untrained Group***	***Trained Group***
#	7	7
ESVI [ml/m^2]	17.85±3.80	24.02±3.84*
EDVI [ml/m^2]	43.70±6.56	69.04±7.77*
CI [L/min.m^2]	1.94±0.45	2.78±0.60*
LVEF [%]	59.38±4.80	65.20±3.94*

TABLE III. Hemodynamic Parameters corresponding to both grups. SVR: Systemic Vascular Resistance (corrected by cardiac cycle, T) [mmHg/ml], TACI: Total Arterial Compliance [ml/mmHg], $E_{LV}I$: Left Ventricular Elastance [mmHg/ml], E_AI: Arterial Elastance [mmHg/ml]. AVC: Ventricular-Arterial Coupling, SWI: stroke work [mmHg.ml], SW_EI and SW_DI: Stroke Work Elastic and dissipative component, SWDR: Stroke Work Damping Ratio. Suffix "I": Indexed by body surface area (BSA). *P<0.05 was considered as statistically signficant

Hemodynamic parameters		
Parameter	***Untrained Group***	***Trained Group***
#	7	7
SVRI/T [mmHg.m^2/ml]	4.00±0.66	1.82±0.35*
TACI [ml/mmHg.m^2]	0.59±0.12	0.94±0.23*
$E_{LV}I$ [mmHg/ml.m^2]	6.23±1.41	3.83±0.65*
E_aI [mmHg/ ml.m^2]	4.02±0.73	1.74±0.39*
AVC	0.66±0.13	0.46±0.08*
SWI [ml.mmHg/m^2]	2725.61±552.53	3440.81±536.24*
SWI_E ml.mmHg/m^2]	2388.29±443.35	2893.24±528.48

SWI_V ml.mmHg/m^2]	337.31±122.22	547.57±43.19*
SWDR	0.14±0.03	0.20±0.04*

IV. DISCUSSION

In this study, SWDR was evaluated in trained individuals (soccer players, a mixture between strength and endurance training), being increased in comparison with the non-trained group. This effect is a consequence of a significant increase of SW_V, which could be related with the viscous mechanical property of AS. To our knowledge, the damping ratio between dissipated and elastic energy (provided to AS in each cardiac cycle) has never been evaluated before in terms of LV PV-loop, as a new measure of interaction between LV and AS. Obtained E_{LV}, E_A and AVC variations (including the other echocardiographic characteristics) were in agreement with previous studies, in which a coupling decrease is observed in trained individuals [12]. Cardiovascular energetic efficiency is optimized by AVC and is tightly controlled at rest, with ranges between 0.5 and 0.6. Therefore, an optimal matching of ventricular and vascular properties is achieved in terms of minimizing oxygen consumption and enhancing ventricular efficiency, rather than SW. This condition can be addressed in the UG group. In non-physiological or stressful conditions, maximization SW is prioritized over efficiency, which causes AVC values to approach to unity [2]. During aerobic exercise, cardiac efficiency is favored over energetic efficiency and, as a result, AVC is reduced, which can be observed in TG [3], [12]. An increase in arterial compliance was also observed in TG as a consequence of aerobic training (which is considered to reduce the arterial load) [13]. However, other authors have reported no stiffness changes between trained and untrained groups of similar age [6], [14].

Regarding SW variations, it is well known resistance exercise increases SW levels. Nevertheless, SWDR provides a 'damping view' to the LV-PV loop, in terms of the viscous effect reflected by AS, which is effectively increased in TG. From a clinical point of view, this TG condition could be considered as a state of maximum cardiovascular reserve. Damping serves to control the steady state resonant response and to attenuate traveling waves in the arterial structure [5]. The AWV, which is mainly affected by VSM, reflects not only energy dissipation during mechanical transduction but could also develop a protective function against pulsatile energy [14]. It is important to highlight that changes in vasomotor tone, which is directly related with changes in wall viscosity [5], affect the relationship between arterial pulse pressure and stroke volume (i.e. E_A) [15]. From the LV PV loop point of view, this condition implies a SW_D variation and hence in SWDR. Accordingly, the obtained results suggest that a decrease in AVC as a consequence of training is accompanied by an increase in the LV damping ratio. This phenomenon is explained by the increment of AWV, which is mainly related with VSM cells and muscle contraction. In this sense, it has been suggested that AWV could be a more sensitive parameter of mechanical characteristics for the assessment of vascular health than arterial stiffness [14]. On the other hand, significant differences were found between age in UG vs. TG. However, blood pressure and TAC can be considered to remain constant within an age range between 20 and 40 years, behaving as a single age group [13]. Moreover, arterial wall viscosity, which is known to increase with age [14] was greater in TG (the younger group). Finally, it should be noted that a linear relationship was used on the PV plane to connect the onset of ejection and its corresponding end, thus separating the PV Loop into SW_E and SW_V. This assumption was established as a formalism determined by the family of lines that start at the beginning of ejection point (EDV; BEP) and delimits each state of the PV loop evolution during the ejection interval. The last state acts as the SW_V boundary. To conclude, an 'estimated' LV PV loop was constructed for the assessment of SWDR, based on echocardiographic and ascending aortic pressure estimations. The validity of the assumptions made, together with the limited number of subjects that were considered, requires further studies to confirm the obtained findings.

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