ORIGINAL ARTICLE

Role of Conduit Volume as Compensating Mechanism for Left Atrial Dysfunction in Severe Aortic Stenosis

Rol del volumen conducido como mecanismo compensador de la disfunción de aurícula izquierda en la estenosis aórtica grave

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ABSTRACT

Background: The left atrium (LA) plays a key role in maintaining stroke volume (SV) in the presence of left ventricular (LV) diastolic dysfunction (DD) through its reservoir, conduit and booster pump function. In normal subjects, the contribution of atrial volume (conduit and booster pump function) to the SV is approximately 60-70%, and the rest is completed by the conduit volume (CV), defined as the blood volume that flows from the pulmonary veins to the LV during passive filling, without producing changes in the atrial volume. In LVDD, when ventricular filling pressures increase and the limits of preload reserve are reached, the LA behaves predominantly as a conduit with reduction of the reservoir, conduit, and booster pump function, resulting in increased CV. Severe aortic stenosis (AS) is characterized by DD in the early stages and LA dysfunction in more advanced stages.
Objective: The aim of the present study was to analyze the role of CV as a compensating mechanism for LA dysfunction to complete LV filling in severe AS.
Methods: A total of 210 patients (pts.), aged 69 ± 11 years, 48% women, with severe AS (aortic valve area index 0.37 ± 0.12 cm^2/m^2) were assessed using Doppler echocardiography. Left atrial function was assessed though LA emptying fraction (LAEF) as the difference between maximum LA volume (maxLAV), which includes conduction and contraction phases, and minimum LA volume (minLAV)/maxLAV ×100, and peak LA strain. The contribution of CV to stroke volume (SV) was estimated as percentage of SV (CV%): SV - (maxLAV - minLAV) /SV × 100. Left atrial volume, SV and LV ejection fraction (LVEF) were calculated using the Simpson's method. Diastolic dysfunction was staged according to the ASE/EACVI recommendations, and the pts. were divided into 3 groups: DD grade I (98 pts.), DD grade II (74 pts.) and DD stage III (38 pts.).
Results: The CV% had a negative correlation with LAEF ($r = -0.57$, $p < 0.0001$) and peak LA strain ($r = -0.38$, $p < 0.001$), and a positive correlation with DD grade ($r = 0.35$, $p < 0.001$). LVEF correlated with LAEF ($r = 0.45$, $p < 0.01$) and CV% ($r = -0.33$, $p < 0.001$). In the DD grade III group, the SV was maintained by the increased CV% despite the significant reduction of LAEF and peak LA strain.
Conclusions: Left atrial dysfunction, expressed as decreased LAEF and peak LA strain, correlates with greater contribution of the CV to the SV (CV%). In patients with severe AS, as DD progresses, the SV is preserved due to increased CV as a compensating mechanism for LA dysfunction.

Key words: Aortic Valve Stenosis - Diastole/physiology - Atrial Function, Left - Heart Atria

RESUMEN

Introducción: La aurícula izquierda (AI) tiene un rol central en el mantenimiento del volumen sistólico (VS) en presencia de disfunción diastólica (DD) del ventrículo izquierdo (VI) a través de la función de reservorio, conducción y contracción. En individuos normales, la contribución del volumen auricular (conducción y contracción) al VS es de aproximadamente 60 – 70%, siendo el resto completado por el volumen conducido (VC) definido como el volumen de sangre que pasa desde las venas pulmonares al VI durante el lleno pasivo, sin producir cambios en el volumen auricular. En la DD del VI, a medida que las presiones de lleno aumentan y se acercan al límite de reserva de la precarga, la AI se comporta predominantemente como un conducto con disminución de las fases de reservorio, conducciòn y contracciòn, con el consiguiente aumento del VC. La estenosis aórtica (EAo) grave se caracteriza por DD en los estadios iniciales y disfunción de la AI en los estadios más avanzados.
Objetivo: Analizar el rol del VC como mecanismo compensador de la disfunción de la AI para completar el lleno del VI en la EAo grave.
Material y métodos: 210 pacientes (pac.) (edad 69 ± 11 años, 48% mujeres) con EAo grave (índice de área valvular 0,37 ± 0,12 cm^2/m^2) fueron estudiados con eco-Doppler. La función de la AI fue evaluada mediante la fracción de vaciado de AI (FVAI) como la

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diferencia entre el volumen máximo (Mx) (incluye las fases de conducción y contracción) y el volumen mínimo (Mn) /Mx x 100 y el *strain* pico de AI. La contribución del VC al volumen sistólico (VS) fue estimada como porcentaje de VS (VC%): VS – (AI Mx – Mn)/ VS x 100. Los volúmenes de AI, el VS y la fracción de eyección del VI (FEVI) fueron calculados por el método de Simpson. El grado de DD fue clasificado de acuerdo con las recomendaciones de la ASE/EACVI y los pacientes fueron divididos en 3 grupos: DD grado I (98 pac.), DD grado II (74 pac.) y DD grado III (38 pac.).

Resultados: El VC% se correlacionó negativamente con la FVAI ($r = -0,57$, $p < 0,0001$), el *strain* pico de AI ($r = -0,38$, $p < 0,001$) y positivamente con el grado de DD ($r = 0,35$, $p < 0,001$). La FEVI se correlacionó con la FVAI ($r = 0,45$, $p < 0,01$) y el VC% ($r = -0,33$, $p < 0,001$). En el grupo DD grado III el VS fue mantenido por el aumento del VC% a pesar de la significativa disminución de la FVAI y el strain pico de la AI.

Conclusión: La disfunción de la AI expresada como la disminución de la FVAI y el strain pico de la AI se correlaciona con un aumento de la contribución del VC al VS (VC%). En pacientes con EAo grave, a medida que la DD progresa, el VS es mantenido a expensas del incremento del VC como un mecanismo compensador de la disfunción de la AI.

Palabras Clave: Estenosis de la válvula aórtica - Diástole/fisiología - Función del Atrio Izquierdo - Atrios cardíacos

INTRODUCTION

Left ventricular (LV) diastolic dysfunction (DD) is an independent predictor of all-cause mortality in the general population, even in preclinical stages. (1, 2) In patients with severe aortic stenosis (AS), a staging classification based on anatomic and functional cardiac damage has been proposed to assess the impact of the valvular heart disease on the cardiac chambers. (3) This classification is based on the concept that the increased afterload secondary to AS causes LV dysfunction (stage 1) that progresses to LV damage and finally to right ventricular damage (stage 4). In stage 1, DD is quantified with an E/e' ratio > 14, indicating increased LV diastolic pressures at rest, which are transmitted to the left atrium (LA) resulting in LA enlargement (stage 2), and then to the pulmonary capillary causing pulmonary hypertension (stage 3) and finally right ventricular dysfunction (stage 4). The key variables recommended for grading DD include E/e' ratio, mitral flow velocities, systolic pulmonary artery pressure and LA volume index (LAVi) > 34 mL/m^2 according to the ASE/EACVI guidelines. (4) LA function has 3 phases, serving as a *reservoir* during ventricular systole, as a *conduit*, and as a *booster pump* during LV diastole. (5, 6) There is a close interaction between the LV and LA in each phase of LA function. LA *reservoir* function is determined by LA relaxation and compliance, RV systolic pressure transmitted to the pulmonary circulation and LV longitudinal systolic function represented by the descent of the atrioventricular plane which, due to flow from the pulmonary veins, causes a progressive increase in LA volume until the maximum volume (maxLAV) is reached (Figure 1). The *conduction* phase begins when the mitral valve opens and blood flows from the LA into the LV; it is influenced by ventricular relaxation and compliance. The *booster pump* phase depends on LA inotropic state, LV end-diastolic pressure and ventricular compliance. After this phase, the LA reaches its minimum volume (minLAV) (Figure 1). Figure 2 shows that the volume of blood provided by the LA, determined by the difference between maxLAV and minLAV (42 mL) is lower than LV filling volume, which is equal to the volume pumped out by the LV known as stroke

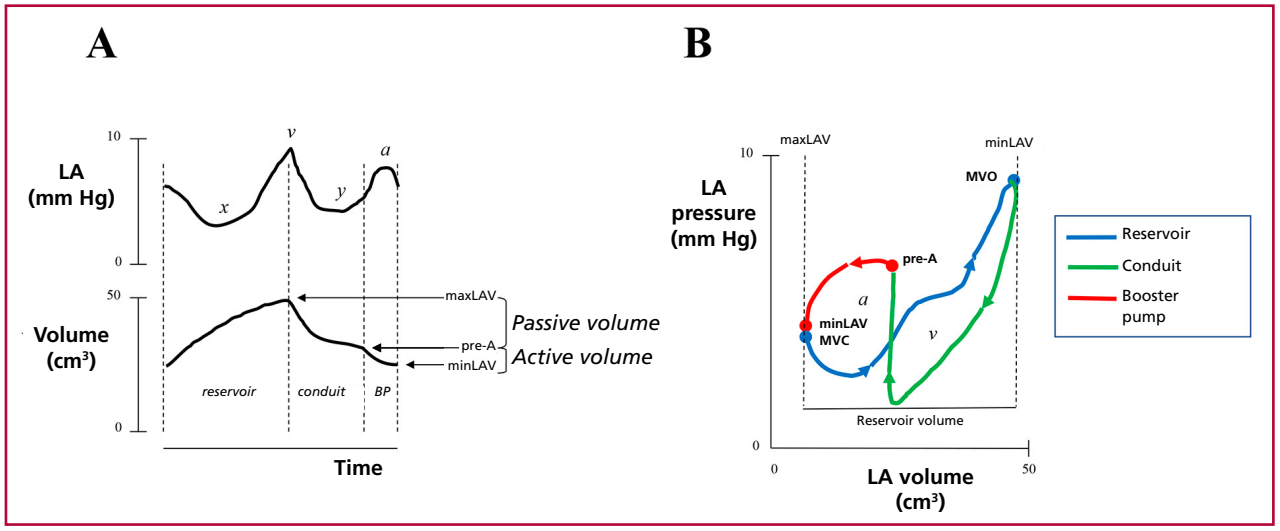


Fig. 1. A. Diagram of left atrial (LA) pressure and LA volume curve as a function of time during the reservoir, conduction and booster pump (BP) phases. maxLAV: maximum left atrial volume; minLAV: minimum left atrial volume. **B.** Left atrial (LA) pressure-volume relationship with the "a" loop and the "v" loop showing the phases with different colors. MVC: mitral valve closure; MVO: mitral valve opening

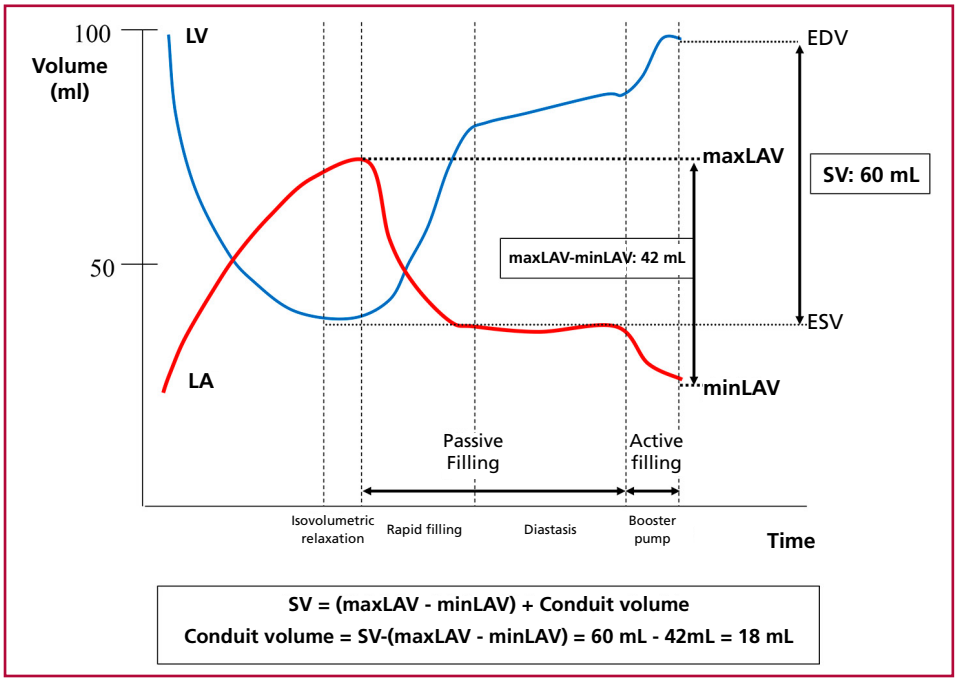


Fig. 2. Left ventricular (LV) and left atrial (LA) pressure curves as a function of time, showing the phases of ventricular diastolic filling. maxLAV - minLAV is the volume provided by the LA (42 mL) to LV filling (60 ml). Conduit volume (CV) completes LV filling (18 mL) and is calculated using the formula described in the figure. EDV: LV end-diastolic volume; ESV: LV end-systolic volume; SV: LV stroke volume which is equal to LV filling volume.

volume (SV) (60 ml). In normal subjects, the contribution of atrial volume (conduit function and booster pump function) to the SV is approximately 60-70%, and the rest is completed by the conduit volume (CV), defined as the blood volume that flows from the pulmonary veins to the LV during passive filling, without producing changes in the atrial volume. (7-10) In LVDD, when ventricular filling pressures increase and the limits of preload reserve are reached, the enlarged LA wil behave predominantly as a conduit with reduction of the reservoir, conduit, and booster pump function resulting in increased CV. In advanced stages of DD, LV filling volume (equivalent to the SV) is largely completed by the CV and the rest by the volume provided by the LA (maxLAV - minLAV). Severe AS is characterized by DD in the early stages and LA dysfunction in more advanced stages.

The aim of the present study was to analyze the role of the CV as a compensating mechanism for LA dysfunction to complete LV filling in severe AS.

METHODS

We prospectively evaluated 210 patients (pts.), aged 69 ± 11 years, 48% women, with severe AS (aortic valve area index 0.37 ± 0.12 cm^2/m^2) using Doppler echocardiography. The study protocol was approved by the Teaching and Research Committee of our institution. Patients with significant calcification of the mitral annulus or with moderate to severe aortic regurgitation or mitral regurgitation were excluded. History of hypertension was considered as the need for antihypertensive treatment. History of ischemic heart disease was based on the presence of one of the following criteria or greater: 1) history of myocardial infarction, percutaneous coronary intervention or myocardial revascularization surgery; 2) coronary artery stenosis > 50% documented by angiography; and 3) akinetic segments documented by echocardiography. Before Doppler echocardiography all the patients underwent anamnesis to detect the presence of coronary risk factors and symptoms, cardiovascular physical examination, and blood pressure measurement.

Table 1. Clinical parameters

Cardiovascular risk factors and comorbidities (%)	
Coronary artery disease	25
Previous myocardial infarction	10
Hypertension	61
Diabetes	17
Dyslipidemia	32
Current smoking	28
Obesity (BMI > 30Kg/m2)	23
Chronic obstructive pulmonary disease	4
Symptoms (%)	
Angina	15
Syncope	3
Class I-II dyspnea	28
Class III-IV dyspnea	50

BMI: body mass index

Doppler echocardography: The study was performed with a ESAOTE Mylab 40 ultrasound machine with a 2.5 to 3 MHz transducer with the patient in the left lateral decubitus position and simultaneous recording of a lead II electrocardiogram. M mode echocardiography and two-dimensional echocardigraphy were used to calculate LV endocardial fractional shortening (eFS), relative wall thickness (RWT), end-diastolic volume (EDV) (estimated by the Simpson's method), end-systolic volume (ESV) and ejection fraction (EF), according to the criteria of the ASE. (11)

The LV mass was calculated using the Devereux formula (12) and was then indexed for body surface area (LVMI).

Peak aortic jet velocity, mean gradient (MG) across the aortic valve and velocity-time integral (VTI) were recorded

Table 2. Echocardiographic parameters of the left ventricle and aortic valve

	All the patients n=210	DD I n=98	DD II n=74	DD III n=38
Age (years)	68 ± 12	69 ± 11	66 ± 13	71 ± 9
Body surface area (m^2)	1.83 ± 0.20	1.81 ± 0.17	1.87 ± 0.23	1.78 ± 0.19
Systolic blood pressure (mm Hg)	129 ± 23	133 ± 21^	129 ± 27	120 ± 19
Diastolic blood pressure (mm Hg)	75 ± 13	77 ± 11 ^	75 ± 14	67 ± 11
Heart rate (beats per minute)	69 ± 11	69 ± 10	69 ± 13	72 ± 11
LV systolic function				
LV diastolic dimension (cm)	5.3 ±0.84	5 ± 0.74 *Δ	5.4 ± 0.71 *	6.2 ± 0.79
LV systolic dimension (cm)	3.6 ± 1	3.2 ± 0.82 *Δ	3.7 ± 0.91 *	4.8 ± 1
Fractional shortening (%)	33 ± 10	36 ± 9 *	33 ± 10 *	22 ± 9
Posterior wall thickness in diastole (cm)	1.2 ± 0.19	1.2 ± 0.18	1.4 ± 0.20	1.2 ± 0.20
Interventricular septal thickness in diastole (cm)	1.3 ± 0.22	1.4 ± 0.18	1.4 ± 0.25	1.2 ± 0.27
Relative wall thickness	0.48 ± 0.11	0.52 ± 0.11 * Δ	0.46 ± 0.09 ^	0.39 ± 0.10
LV mass index (gr/m^2)	162 ± 45	149 ± 41 * Δ	167 ± 49 π	189 ± 38
LV ejection fraction, %	55 ± 18	62 ± 14 * Δ	53 ± 17 *	33 ± 14
LV end-systolic volume (mL)	64 ± 19	64 ± 19 ^	67 ± 20 ^	53 ± 19
Stroke volume index (mL/m^2)	35 ± 11	35 ± 10 π	36 ± 11π	30 ± 10
Transaortic flow rate (mL/s)	188 ± 49	190 ± 45 π	195 ± 50 π	164 ± 51
LV global systolic strain (%)	- 14 ± 5	-16 ± 3 * Δ	- 14 ± 5 *	- 8 ± 2
Aortic stenosis				
Peak aortic jet velocity (m/s)	4.1 ± 0.9	4.15 ± 0.9 π	4.24 ± 0.9 ^	3.7 ± 0.9
Mean aortic gradient (mm Hg)	42 ± 19	42 ± 19	44± 19 π	34 ± 19
Dimensionless index	0.21 ± 0.06	0.21 ± 0.06	0.21 ± 0.06	0.19 ± 0.07
Aortic valve area (cm^2)	0.68 ± 0.20	0.68 ± 0.21	0.68 ± 0.20	0.65 ± 0.20
Aortic valve area index (cm^2/m^2)	0.37 ± 0.12	0.38 ± 0.12	0.37 ± 0.11	0.37 ± 0.12
Valvulo-arterial impedance (mm Hg/mL/m^2)	5 ± 1.5	5 ± 1.4	4.9 ± 1.5	5.7 ± 1.6
Energy loss index (cm^2/m^2)	0.42 ± 0.15	0.43 ± 0.15	0.42 ±0.14	0.42 ± 0.15
* $p < 0.0001$ vs. DD III Δ $p < 0.01$ vs. DD II π $p < 0.05$ vs. DD III ^ $p < 0.01$ vs. DD III				

LV: Left ventricular
Values are expressed as mean ± standard deviation

with continuous Doppler echocardiography from the apical view, right parasternal view, subcostal view and suprasternal view. Pulsed wave Doppler was used to determine LV outflow tract flow from the 5-chamber view. The dimensionless index was estimated as the ratio of the LV outflow tract time-velocity integral to that of the aortic valve jet. The effective aortic valve area (AVA) was measured by the continuity equation, and the AVA index, valvulo-arterial impedance and energy loss index were also calculated according to the ASE. (13) Stroke volume was calculated by multiplying the cross-sectional area of the LV outflow tract per the velocity time integral of flow across that area, SV index was estimated as the ratio between SV and body surface area, and transaortic flow rate was calculated by dividing the SV by the LV systolic ejection period. Left ventricular ejection fraction (LVEF) was estimated by the biplane Simpson's method and relative wall thickness (RWT) as 2×end-diastolic posterior wall thickness/end-diastolic LV dimension.

Transmitral flow velocity was recorded by placing the pulsed Doppler sample volume at the level of the mitral valve tips in the 4-chamber view to obtain peak E velocity and peak A velocity to calculate E/A ratio. (14) Then, a tissue Doppler imaging sample volume was placed at the lateral and septal portions of the mitral annulus to acquire peak e' velocity, and the average of both was used to determine E/e' ratio. (15) Peak tricuspid regurgitation velocity was recorded with continuous Doppler, and this parameter plus the right atrial pressure estimated through the diameter and collapse of the inferior vena cava were used to estimate the systolic pulmonary artery pressure. In 48 patients, longitudinal strain was estimated with two-dimensional speckle tracking echocardiography from the apical four-chamber, two-chamber and apical long-axis views, using the software provided by the device. The results from the 3 views were averaged because the software available does not calculate the global strain automatically.

Left atrial function assessment: maxLAV and minLAV were obtained from the 4-chamber and 2-chamber views with the Simpson's method. The difference between both volumes (maxLAV - minLAV) represents the volume contributed by the LA to LV filling. Left atrial volume index was calculated as the ratio between maxLAV and body surface area (BSA). Left atrial emptying fraction (LAEF) was estimated according to the following formula: LAEF = [(maxLAV - minLAV)/maxLAV] × 100. Conduit volume (CV) (Figure 2) -the blood volume that flows from the pulmonary

Table 3. Left ventricular diastolic function and left atrial function

	All the patients n=210	DD I n=98	DD II n=74	DD III n=38
LV diastolic function				
Peak E wave velocity (m/s)	0.82 ± 0.24	0.66 ± 0.16 # ´	0.96 ± 0.20	1 ± 0.20
Peak A wave velocity (m/s)	0.82 ± 0.24	1 ± 0.23 # ´	0.77 ± 0.22 #	0.35 ± 0.10
Mitral E/A ratio	1.25 ± 0.90	0.66 ± 0.13 # ´	1.29 ± 0.31 #	3 ± 0.80
Isovolumetric relaxation time (ms)	82 ± 26	101 ± 19 # ´	68 ± 18 *	53 ± 10
Deceleration time (ms)	221 ± 96	278 ± 87 # ´	187 ± 78 *	125 ± 23
Peak e' velocity derived from tissue Doppler imaging (cm/s)	5.4 ± 1.7	5.2 ±0.5	5.7 ± 1.8	5.3 ± 1.6
E/e' ratio	15 ± 7	14 ± 7 ^ Δ	17 ± 7	18 ± 8
Systolic pulmonary artery pressure (mm Hg)	49 ± 16	36 ± 7 # Δ	48 ± 16 ^	60 ± 12
LA function				
maxLAV (mL)	98 ± 33	86 ± 34 # ´	104 ± 29 Δ ^	122 ± 25
minLAV (mL)	65 ± 31	52 ± 29 # ´	68 ± 25 Δ ^	100 ± 23
maxLAV - minLAV (mL)	35 ± 13	34 ± 11 ^	37 ± 14 ^	28 ± 12
LA emptying fraction (%)	36 ± 15	42 ± 11 # Δ	36 ± 13 #	16 ± 12
LA volume index (ml/m²)	54 ± 17	47 ± 16 # Δ	56 ± 15 #	69 ± 14
Conduit volume (mL)	24 ± 17	20 ± 13 #	23 ± 18 #	39 ± 19
Conduit volume %	39 ± 23	33 ± 16 #	36 ± 22 #	65 ± 26
Peak LA strain (%)	21 ± 9	23 ± 6 ^	22 ± 11 ^	13 ± 2
^ p < 0.01 vs. DD III Δ p < 0.01 vs. DD II # p < 0.0001 vs. DD III * p < 0.001 vs. DD III ´ p < 0.0001 vs. DD II				

LV: left ventricular. LA: Left atrial. LAV: Left atrial volume.
Values are expressed as mean ± standard deviation

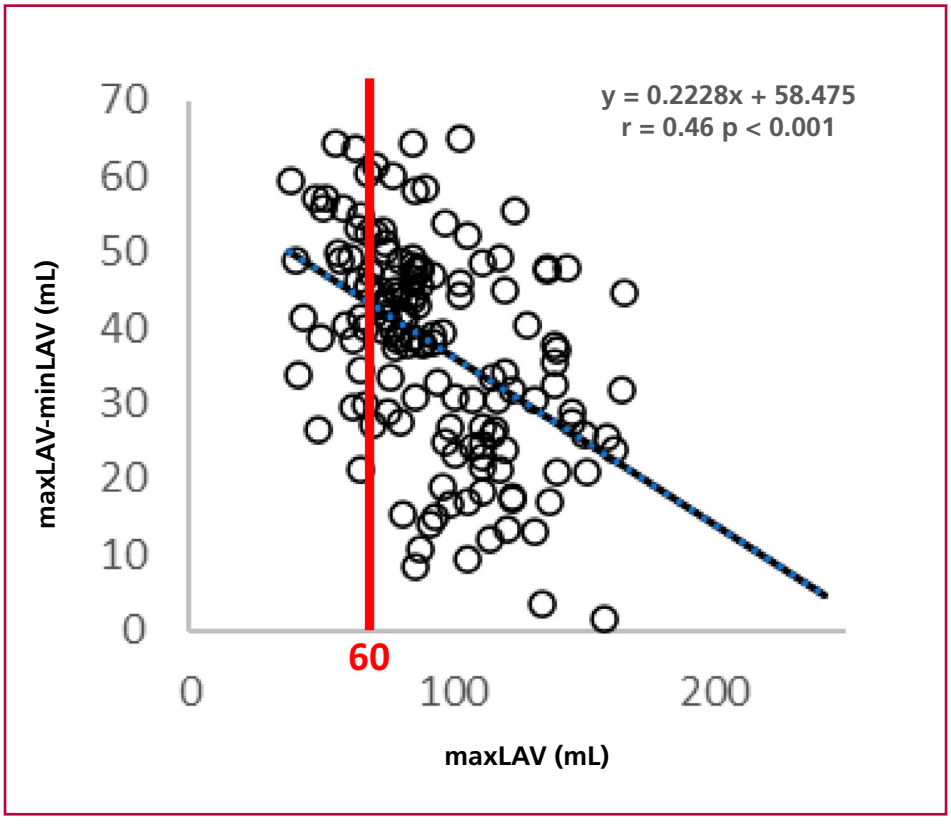


Fig. 3. Correlation between maxLAV - minLAV and MaxLAV.

veins to the LV during without producing changes in the LA volume- was also calculated and expressed in absolute values and as a percentage of SV (CV%): [(SV - (maxLAV - minLAV)) /SV] × 100. Global peak LA strain was obtained with two-dimensional speckle tracking echocardiography in 48 patients; the software provided by the equipment was used to measure LV global longitudinal strain from the 4-chamber view, optimizing the visualization to obtain the maximum volume. Then, the endocardial border of the LA was outlined, excluding the LA appendage and pulmonary veins, and manual corrections were made if necessary. (16) The average of three consecutive measurements was considered for each parameter.

Diastolic dysfunction was staged according to the ASE/EACVI recommendations considering the E/A ratio, E/e' ratio, pulmonary artery systolic pressure and LAVi.

Patients were divided into 3 groups: DD grade I (n = 98), DD grade II (n = 74) and DD grade III (n = 38).

Statistical analysis

All the statistical calculations were performed using Statistix 10 software package. Continuous variables were expressed as mean ± standard deviation. The groups were compared using analysis of the variance and correlations were analyzed using Pearson's correlation coefficient (r). A p value < 0.05 was considered statistically significant.

RESULTS

Table 1 shows the cardiovascular risk factors, comorbidities and symptoms of the patients evaluated. There were no significant differences in age and body surface area among the three DD groups. (Table 2). Systolic and diastolic blood pressure were lower in DD III versus DD I. There were no differences in heart rate.

LV systolic function: LV diastolic and systolic dimensions increased progressively from DD I to DD III. (Table 2) Left ventricular endocardial fractional shortening was significantly decreased in patients with DD 3. According to RWT and LVMI, concentric hypertrophy predominated in the groups DD I and II, and eccentric hypertrophy in DD III. There was a significant decrease in LVEF from DD I to DD III. Nevertheless, SV, SV index and aortic flow were decreased only in the group DD III, with no significant differences between DD I and DD II. Left ventricular longitudinal strain decreased from DD I to DD III, with significant differences among the three groups.

Aortic stenosis: the severity of AS was similar in the three groups when considering the dimensionless index, AVA index, valvulo-arterial impedance and energy loss index. Peak aortic jet velocity and MG were lower in the group DD II in accordance with lower SV index and transaortic flow in this group. (Table 2)

LV diastolic function: Table 3 shows the parameters of diastolic function. According to the staging in three groups od DD proposed by the ASE/EACVI, the E/A ratio and the E/e' ratio increased from DD I to DD III, while isovolumetric relaxation time and deceleration time had an opposite behavior. Peak e' velocity on pulsed tissue Doppler imaging showed a non-significant reduction among the three groups. Systolic pulmonary artery pressure increased significantly from the DD I to DD III.

LA function: (Table 3) there was a significant increase in maxLAV, minLAV and LAVi from DD I to DD III. However, the difference between both volumes (maxLAV and minLAV), the volume contributed by the LA to LV filling, was reduced in patients with DD III. Figure 3 illustrates the negative correlation between maxLAV and the volume contributed by the LA to ventricular filling (maxLAV - minLAV). It can be seen that after 60 ml, LA enlargement cannot compen-

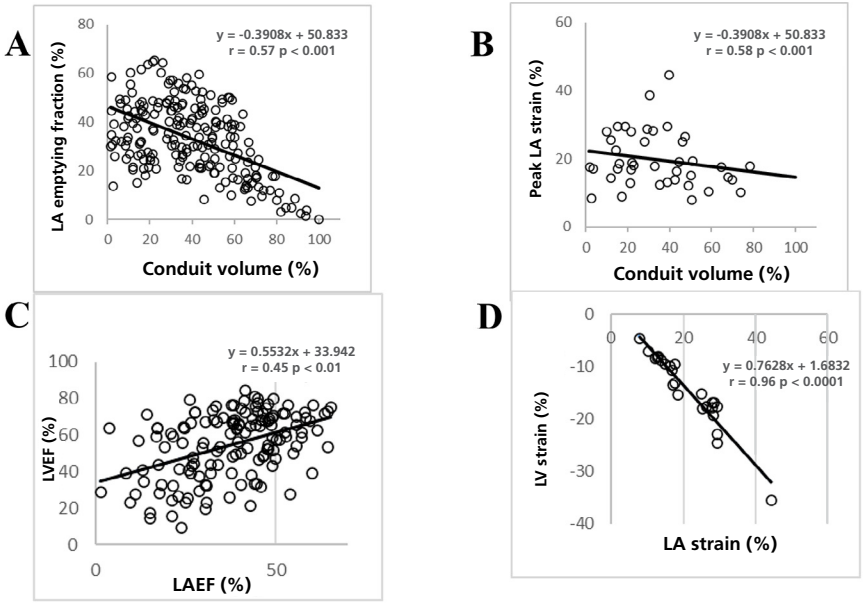
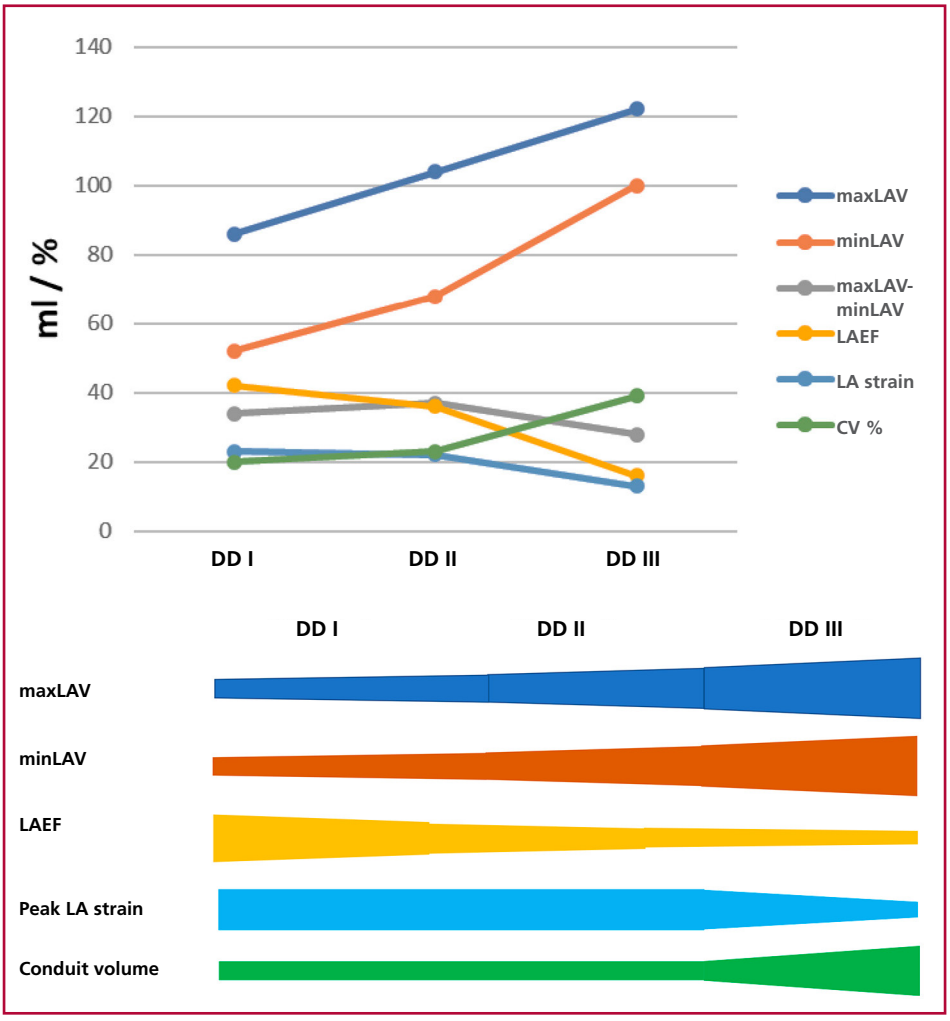


Fig. 4. A. Correlation between LA emptying fraction and conduit volume. **B.** Correlation between LA peak strain and conduit volume. **C.** Correlation between left ventricular ejection fraction (LVEF) and left atrial emptying fraction (LAEF). D. Correlation between LV strain and LA strain

Fig. 5. A and **B**: See text for explanation.



LAEF: left atrial emptying fraction CV: conduit volume DD: diastolic dysfunction

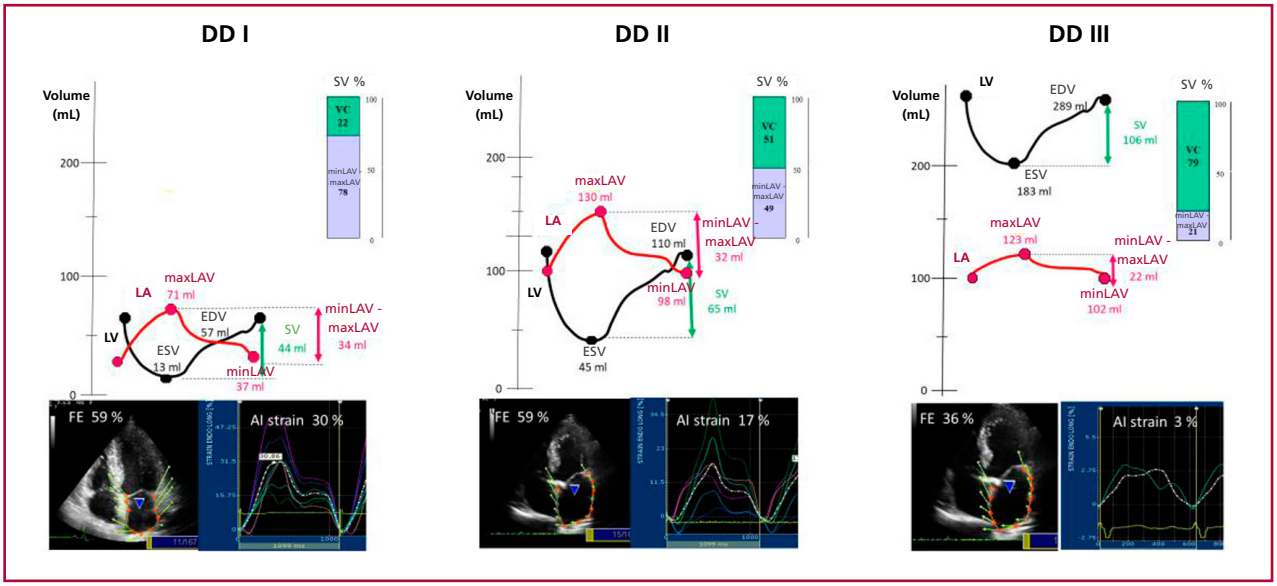


Fig. 6. LV and LA volume curves for each diastolic dysfunction (DD) grade. The bar at the top right of each DD stage corresponds to the SV components. The percentage of conduit volume (CV) that completes the SV increases as DD progresses. The lower part shows atrial strain curves of the different groups. The abbreviations are similar to those of the previous figures

sate for the decrease in maxLAV - minLAV, indicating the Frank-Starling mechanism at the atrial level, and a decompensation phase starts after the line reaches the point of 60 ml. There is a slow reduction in LAEF from DD I to DD III with significant differences across the three groups. Left atrial strain performance was different, as it decreased in patients with DD III but there were no significant differences between patients with DD I and DD II.

Conduit volume: CV and CV% were significantly increased in the group DD III, without differences between DD I and DD II. (Table 3) The CV% had a negative correlation with LAEF ($r = -0.57$, $p < 0.0001$) (Figure 4 A), and peak LA strain ($r = -0.58$, $p < 0.001$) (Figure 4 B) and a positive association with DD stage ($r = 0.35$ $p < 0.001$). LVEF correlated with LAEF ($r = 0.45$, $p < 0.01$) (Figure 4 C) and CV% ($r = - 0.33$, $p < 0.001$). In group DD III, SV was maintained by the increased CV% despite the significant reduction of LAEF and peak LA strain. Left ventricular strain had a close correlation with LA strain (Figure 4 D). Figure 5 A and B show how maxLAV and minLAV increase as DD progresses, while LAEF decreases. Left atrial strain performance is similar to that of maxLAV - minLAV, with a significant reduction in DD III and no variations in DD I and DD II (Figure 5 A and B). The CV% compensates for the reduction of maxLAV - minLAV (and of LA strain), with a significant increase in DD III, thus completing LV filling which would otherwise remain incomplete if it only depended on maxLAV - minLAV (Figure 5 A and B). Figure 6 shows LV and LA volume curves, using maxLAV, minLAV, maxLAV - minLAV, EDV, ESV and average SV for each grade of DD as reference. The bars show the percent contribution of the volume provided by the LA (maxLAV - minLAV) SV and CV to the SV (similar to LV filling volume). MaxLAV - minLAV decreases from DD stage I to III while CV increases.

DISCUSSION

The main finding of the present paper is that in patients with severe AS and severe diastolic dysfunction (DD grade III) and LA dysfunction (decreased LAEF and atrial strain), ventricular diastolic filling volume is mostly made up of the CV, which is the blood volume passing from the pulmonary veins to the LV, without modifying LA volume. (10) Left atrial volume index is the standard determination performed during conventional Doppler echocardiography, and is one of the four elements for assessing LV diastolic function, together with the E/A ratio, E/e'ratio and systolic pulmonary artery pressure. Besides the structural characteristics of the LA determine maxLAV, used to estimate LAVi, the atrium is a dynamic structure with volume variations throughout the entire cardiac cycle, which can be assessed with minLAV, LAEF and atrial strain. Maximum LAV reflects the chronic increase of diastolic pressures and has prognostic implications, but does not change significantly when diastolic pressures become normal as it occurs with LAEF or strain, (5) and is also influenced by LV longitudinal function through the descent of the mitral plane. For this reason, minLAV might be a better marker of LA function since it is measured in the LV at end diastole when the LA is directly exposed to LV end-diastolic pressure. (17,18) Peak LA strain and maxLAV have demonstrated correlations with invasive determination of LV diastolic pressures. (19) O'Connor et al. evaluated atrial strain in 52 patients with AS and in 20 normal subjects using tissue Doppler echocardiography and found a reduction in reservoir, conduit and booster pump function that correlated with mitral E-wave deceleration time and E/e' ratio. (20) Meimoun et al. analyzed 102 patients with moderate and severe AS and found that LA strain and LA distensibility (a parameter similar to LAEF but with minLAV as denominator) were associated with LV dysfunction, severe AS and hospitalization due to heart failure or all-cause mortality. (21) According to our findings, as DD progresses, maxLAV and minLAV increase, but with a reduction in maxLAV- minLAV and LAEF (Figure 5 A and B). This suggests that the Frank-Starling mechanism has a "compensating" effect at the atrial level when DD progresses from stage I to stage II, and a "decompensating" effect when it progresses from DD stage II to stage III. Left atrial emptying fraction and LA strain decreased 62 % and 44 % (considering average values) when comparing DD I with DD III, respectively, while SV decreased by only 17 % due to increased CV% (Figure 5 A and B). The CV is a compensating mechanism when the elevated diastolic pressures produce LA dysfunction, as evidenced by a reduction in LAEF and atrial strain, (8) and should be considered in the evaluation of DD. However, this aspect is rarely mentioned in reviews on LA structure and function or in the guidelines for the evaluation of diastolic function. The high correlation between LV strain and LA strain ($r = -0.96$) (Figure 4 D) would be explained as the LV and LA share the mitral annulus, which is one of the determinants of both LV longitudinal function and LA function. Therefore, a LV with reduced strain is expected to be accompanied by reduced LA strain, and the CV will complete LV filling to compensate for atrial dysfunction.

CONCLUSIONS

Left atrial dysfunction, expressed as decreased LAEF and peak LA strain, correlates with greater contribution of the CV the SV (CV%). In patients with severe AS, as DD progresses the SV is preserved due to increased CV as a compensating mechanism for LA dysfunction.

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