



HAL
open science

Left atrial strain determinants and clinical features according to the heart failure stages. New insight from EACVI MASCOT registry

Giovanni Benfari, Giulia Elena Mandoli, Julien Magne, Marcelo Haertel Miglioranza, Roberta Ancona, Vlatka Reskovic Luksic, Maria Concetta Pastore, Ciro Santoro, Blazej Michalski, Alessandro Malagoli, et al.

► To cite this version:

Giovanni Benfari, Giulia Elena Mandoli, Julien Magne, Marcelo Haertel Miglioranza, Roberta Ancona, et al.. Left atrial strain determinants and clinical features according to the heart failure stages. New insight from EACVI MASCOT registry. *International Journal of Cardiovascular Imaging*, 2022, 38 (12), pp.2635-2644. 10.1007/s10554-022-02669-x . hal-03886593

HAL Id: hal-03886593

<https://hal.science/hal-03886593>

Submitted on 2 Jun 2023

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License



Left atrial strain determinants and clinical features according to the heart failure stages. New insight from EACVI MASCOT registry

Giovanni Benfari¹ · Giulia Elena Mandoli² · Julien Magne^{3,4} · Marcelo Haertel Miglioranza⁵ · Roberta Ancona⁶ · Vlatka Reskovic Luksic⁷ · Maria Concetta Pastore² · Ciro Santoro⁸ · Blazej Michalski⁹ · Alessandro Malagoli¹⁰ · Denisa Muraru¹¹ · Erwan Donal¹² · Bernard Cosyns¹³ · Thor Edvardsen^{14,15} · Bogdan Alexandru Popescu¹⁶ · Matteo Cameli² on behalf of MASCOT investigators

Received: 9 March 2022 / Accepted: 30 May 2022 / Published online: 1 July 2022
© The Author(s) 2022

Abstract

Few studies analyzed left atrial (LA) peak atrial longitudinal strain (PALS) determinants, particularly across heart failure (HF) stages. We aimed to analyze the pathophysiological and clinical PALS correlates in a large multicentric prospective study. This is a multicenter prospective observational study enrolling 745 patients with HF stages. Data included PALS and left ventricular global longitudinal strain (LV-GLS). Exclusion criteria were: valvular prosthesis; atrial fibrillation; cardiac transplantation; poor acoustic window. Median global PALS was 17% [24–32]. 29% of patients were in HF-stage 0/A, 35% in stage-B, and 36% in stage-C. Together with age, the echocardiographic determinants of PALS were LA volume and LV-GLS (overall model $R^2=0.50$, $p<0.0001$). LV-GLS had the strongest association with PALS at multivariable analysis (beta: -3.60 ± 0.20 , $p<0.0001$). Among HF stages, LV-GLS remained the most important PALS predictor ($p<0.0001$) whereas age was only associated with PALS in lower HF-stage 0/A or B ($R=-0.26$ $p<0.0001$, $R=-0.23$ $p=0.0001$). LA volume increased its association to PALS moving from stage 0/A ($R=-0.11$; $P=0.1$) to C ($R=-0.42$; $P<0.0001$). PALS was the single most potent echocardiographic parameter in predicting the HF stage (AUC for B vs. 0/A 0.81, and AUC vs. 0/A for C 0.76). PALS remained independently associated with HF stages after adjusting for ejection fraction, E/e' ratio, and mitral regurgitation grade ($p<0.0001$). Although influenced by LV-GLS and LA size across HF stages, PALS is incrementally and independently associated with clinical status. LA function may reflect a substantial part of the hemodynamic consequences of ventricular dysfunction.

Keywords Atrial function · Heart failure · Echocardiography

Introduction

Left atrial (LA) peak longitudinal strain (PALS) can be easily obtained by speckle tracking echocardiography (STE) and reliably reflects the LA phasic function [1]. PALS has demonstrated association with major cardiovascular outcomes in several clinical settings including heart failure (HF) [2–5]. However, only a few studies on healthy individuals have analyzed PALS pathophysiological determinants [6–8], and no evidence on the spectrum of HF stages is available.

The LA function mirrors the elevation of left ventricular (LV) filling pressure [9], is influenced by LV performance

[10], and can be a buffer for volume overload as in the case of functional mitral regurgitation [11, 12]. These factors are frequently present in various combinations in HF and may generate complex pathophysiological interactions. Furthermore, whether PALS determinants are similar in all the HF stages has never been explored, leaving doubts on its clinical value's universality in patients with HF.

The present study aims to analyze PALS pathophysiological and clinical correlates in a large multicentric prospective study, including comprehensively characterized HF patients from stage 0 to C.

✉ Giovanni Benfari
giovanni.benfari@gmail.com

Extended author information available on the last page of the article

Methods

Study cohort

From July to October 2018, the European Association of Cardiovascular Imaging (EACVI) Heart Imagers of Tomorrow (HIT) Members and/or Ambassadors experienced in echocardiography, who agreed to participate, were asked to collect clinical and echocardiographic data in various HF stages. The complete protocol of the original study is reported elsewhere [13]. Briefly, the images were acquired using machines from a single vendor (GE Medical Systems, Milwaukee, WI). HF stages were defined according to recommendations as Stage-A, for patients at risk for HF but without current or prior symptoms or signs of HF and structural or biomarkers evidence of heart disease. Stage-B, for patients without current or prior symptoms or signs of HF, but evidence of structural heart disease or abnormal cardiac function, or elevated natriuretic peptide levels. HF Stage-C, for patients with current or prior symptoms and/or signs of HF caused by a structural and/or functional cardiac abnormality [14]. We also included patients without CV risk factors (i.e., healthy subjects) labeled as stage 0. Exclusion criteria were: unfeasible measurements of both LA and LV strain, valvular prosthesis; atrial fibrillation; cardiac transplantation; poor acoustic window (but not sub-optimal). Institutional review board approval was obtained for the study in each center, and all subjects signed the informed consent. All procedures were conducted in accordance with the Declaration of Helsinki.

Standard echocardiography and clinical variables

A complete clinical evaluation was performed at the time of the enrollment including a comprehensive cardiovascular risk factor assessment and evaluation of major comorbidities. Each echocardiogram was performed using a high-quality machine equipped with a 1.5- and 3.6-MHz transducer. The LV and LA volumes were assessed from apical four- and two-chamber views using the biplane modified Simpson's rule, according to current recommendations [15]. The LV mass was assessed from 2D images using the truncated ellipsoid technique and subsequently indexed for body surface area. The diastolic function was assessed using pulsed Doppler and Tissue Doppler Imaging according to recommendations [16]. Mitral, aortic, and tricuspid valve disease were evaluated and graded using an integrated multiparametric approach [16].

Speckle tracking echocardiography

A frame rate of 40–80 fps was required for the STE measurements, and images were analyzed by semi-automatic software (EchoPAC, GE, USA). Two different

echocardiographers, blinded to each other, performed the measurements in each center. A predefined approach was adopted by all centers for LA strain measurements [17]. PALS was obtained from apical four- and two-chamber views and then averaged (Fig. 1A).

LV strain quantification was assessed by an endocardial point-and-click approach, the ROI was manually defined and eventually modified, in each apical view (four-, two- and three-chambers). A total of 18 segments were obtained, six for each view, and GLS reported (Fig. 1B). Advanced measurements were performed by an expert physician and a cardiologist in training, blinded from each other measures.

Statistical analysis

Patients were divided into three groups according to HF stages. The normality of the distribution was assessed using the Shapiro Wilk test. Data are summarized as means \pm SD, median and interquartile range (for continuous variables), or numbers and percentages (for qualitative variables) as appropriate. Comparisons across patient groups were performed using analysis of variance (ANOVA followed by the post hoc Bonferroni test for multiple comparisons), Wilcoxon test, or Chi-squared test. PALS determinants were selected according to their univariable association with PALS and physiological plausibility. Subsequently, to identify the parameters with an independent association to PALS, a multiple linear regression analysis was performed (using PALS as a continuous dependent variable) as well as logistic regression analysis (using PALS above vs. below the median cohort's value). To further validate the results, a neural network (66% training, 33% validation) model was applied.

PALS clinical significance was tested with multinomial logistic regression analysis using HF stages (0 and A, B, C) or NYHA class (I vs. \geq II) as the dependent variables; the area under the curve (AUC) is reported. All analyses were performed using JMP®, Version 14. SAS Institute Inc., Cary, NC. The significance level was set at 0.05 for all analyses.

Results

Characteristics of the study cohort

A total of 745 with complete clinical and echocardiographic evaluation formed the study cohort. Clinical and echocardiographic characteristics are presented in Table 1. The median age was 63 [50–72] years, 58% male. There was a balanced proportion of HF stages: stage 0/A in 29% (n = 214), stage B in 35% (n = 263), and stage C in 36% (n = 268). Despite similar sex distribution and body surface area, multiple clinical and echocardiographic characteristics differ significantly

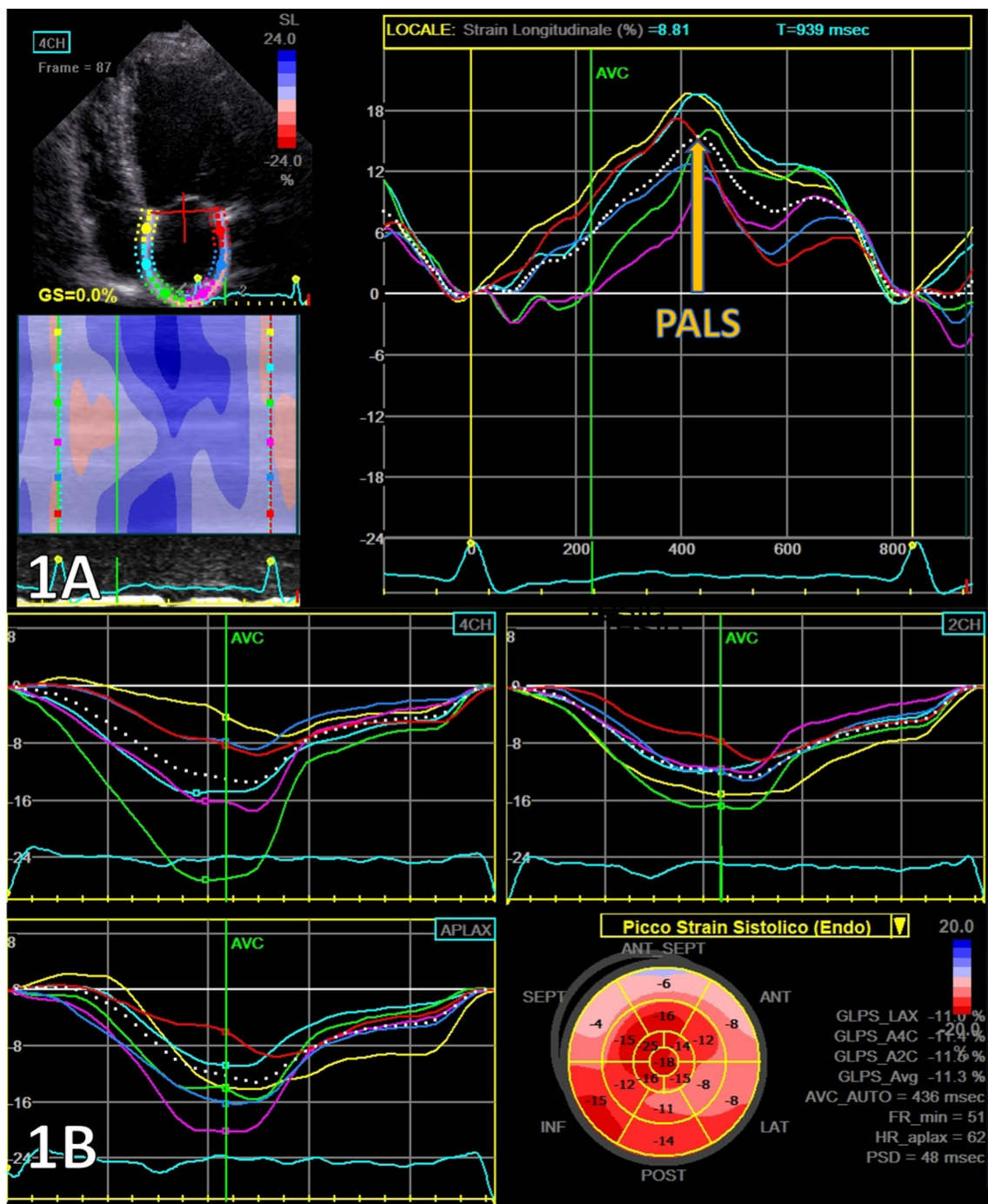


Fig. 1 Representative example of two-dimensional STE-derived PALS measurements **A** and LV GLS **B** from an apical four-chamber view

across the HF stages. In particular, PALS values were significantly lower from stage 0/A to stage C ($p < 0.0001$) as shown in the Supplementary Fig. 1.

Determinants of PALS in the whole cohort

The major echocardiographic features associated with PALS were age ($R = -0.38$, $p < 0.0001$), LAVI

($R = -0.53$, $p < 0.0001$), and LV GLS ($R = -0.56$, $p < 0.0001$) (Fig. 2). Univariable and multivariable regression analysis are presented in Table 2 for PALS as a continuous variable (overall multivariable model $R^2 = 0.50$, $p < 0.0001$) as well as for PALS above the cohort median value, using a neural network to validate the prediction provided similar results ($R^2 = 0.53$ for the patients in the training cohort and $R^2 = 0.52$ for the validation cohort).

Table 1 Clinical and echocardiographic characteristics across HF stages

Clinical variables	Overall (n=745)	HF stage 0/A (n=214; 29%)	HF stage B (n=263; 35%)	HF stage C (n=268; 36%)	p value
Age, y	63 [50–72]	47.5 [34.8–61]	64 [54–72]	70 [61–78]	<0.0001
Men, n (%)	434 [58]	117 [55]	158 [60]	159 [60]	0.4
BSA, m ²	1.84±0.20	1.83±0.20	1.86±0.19	1.84±0.22	0.3
Diabetes, n (%)	139 [19]	15 [17]	42 [20]	82 [31]	<0.0001
Dyslipidemia, n (%)	226 [30]	27 [13]	80 [30]	119 [44]	<0.0001
HT, n (%)	360 [48]	44 [21]	142 [54]	174 [65]	<0.0001
Heart rate (bpm)	69±12	69±11	68±10	70±13	0.07
SBP (mmHg)	130 [118–140]	123 [112–132]	130 [120–140]	130 [118–141]	<0.0001
DBP (mmHg)	80 [70–86]	79 [70–84]	80 [70–89]	80 [70–87]	0.3
Echocardiography					
RWT	40 [33–49]	37 [33–42]	41 [35–48]	44 [34–50]	<0.0001
IVS (mm)	11 [9–12]	9 [8–10]	11 [10–12]	12 [10–13]	<0.0001
PW (mm)	10 [9–11]	9 [8–10]	10 [9–11]	11 [9–12]	<0.0001
LV mass index (g/m ²)	97 [76–122]	74 [62–85]	103 [88–123]	118 [94–140]	<0.0001
EDV index (mL/m ²)	54 [45–67]	51 [43–58]	55 [44–68]	60 [48–79]	<0.0001
ESV index (mL/m ²)	23 [18–31]	19 [16–23]	24 [19–31]	28 [19–43]	<0.0001
LV-EF (%)	58 [50–64]	61 [57–66]	57 [49–62]	53 [40–61]	<0.0001
LAVI max bipl (mL/m ²)	32 [25–42]	24 [21–30]	33 [26–41]	41 [33–55]	<0.0001
E/A ratio	1.09 [0.76–1.58]	1.24 [0.98–1.66]	0.92 [0.71–1.35]	1.00 [0.71–1.76]	<0.0001
E/e' ratio	9.2 [6.9–13]	7.04 [5.84–8.31]	9.2 [6.9–11.5]	12.9 [9.1–17.4]	<0.0001
Mod/severe AS	116 (16)	0 (0)	45 (17)	71 (26)	<0.0001
Mod/severe MR	118 (16)	0 (0)	40 (15)	78 (29)	<0.0001
PALS (%)	17 [14–32]	33 [26–40]	24 [19–31]	18 [12–24]	<0.0001
LV-GLS (%)	-18 [20–15]	-20 [21–18]	-18 [20–15]	-16 [19–12]	<0.0001

Data are expressed as median [IQR] or mean ± DS

AS aortic stenosis; BSA body surface area; DBP diastolic blood pressure; EDV end-diastolic volume; EF ejection fraction; ESV end-systolic volume; GLS global longitudinal strain; HF heart failure; HT hypertension; IVS inter ventricular septum; LA left atrial; LAVI left atrial volume index; LV left ventricular; MR mitral regurgitation; PALS peak atrial longitudinal strain; PW pulsed wave; RWT relative wall thickness; SBP systolic blood pressure

At the univariable analysis, E/e' was significantly associated with PALS ($R = -0.46$, $p < 0.0001$). However, adding E/e' to the other determinants in a nested regression model did not significantly increase the PALS prediction (R^2 grew from 0.50 to 0.51). Therefore E/e' was not included in the final model. Interestingly, no meaningful association was noted between PALS and diastolic blood pressure or heart rate; a complete list of PALS echocardiographic correlates is presented in Supplementary Table 1. Repeating the analysis using the advanced echocardiographic measurements did not affect the results (multivariable PALS prediction R^2 was 0.52, $p < 0.0001$).

The LV GLS showed the strongest correlation with PALS, as illustrated in Fig. 3: the cohort was also divided into four groups based on median PALS (\leq vs. $>$ 25%) and GLS (\leq vs. $>$ 18%). Concordance (preserved PALS and GLS or reduced PALS and GLS) was present in 69% of cases. In the remaining (31%) so-called discrepant cases, reduced PALS in the presence of GLS above the median was the predominant presentation (21% of cases), and only 10% of

the cohort presented preserved PALS and reduced GLS with values clustered towards the fitting line.

Determinants of PALS according to HF stages

The relative importance of each PALS determinant was analyzed according to the HF stages as illustrated in Fig. 4. LV GLS remains steadily the most critical predictor in any stage; age was particularly important in stage 0/A and showed no role in HF stage C (p for interaction = 0.03). Conversely, LAVI showed a modest relationship with PALS in stage 0/A and gained more importance moving to stage B and C. Again, adding E/e' increased the model prediction minimally only in stage C (R^2 grew from 0.39 to 0.41). Among the 268 patients in HF stage C, 67 (25%) had ischemic etiology, 85 (32%) related to systemic hypertension, 67 (25%) to valvular heart disease, and the remaining 49 (18%) were labeled as non-ischemic or mixed etiology. Interestingly, there was no interaction between the HF etiology and the PALS-LV GLS relationship (p for interaction = 0.6).

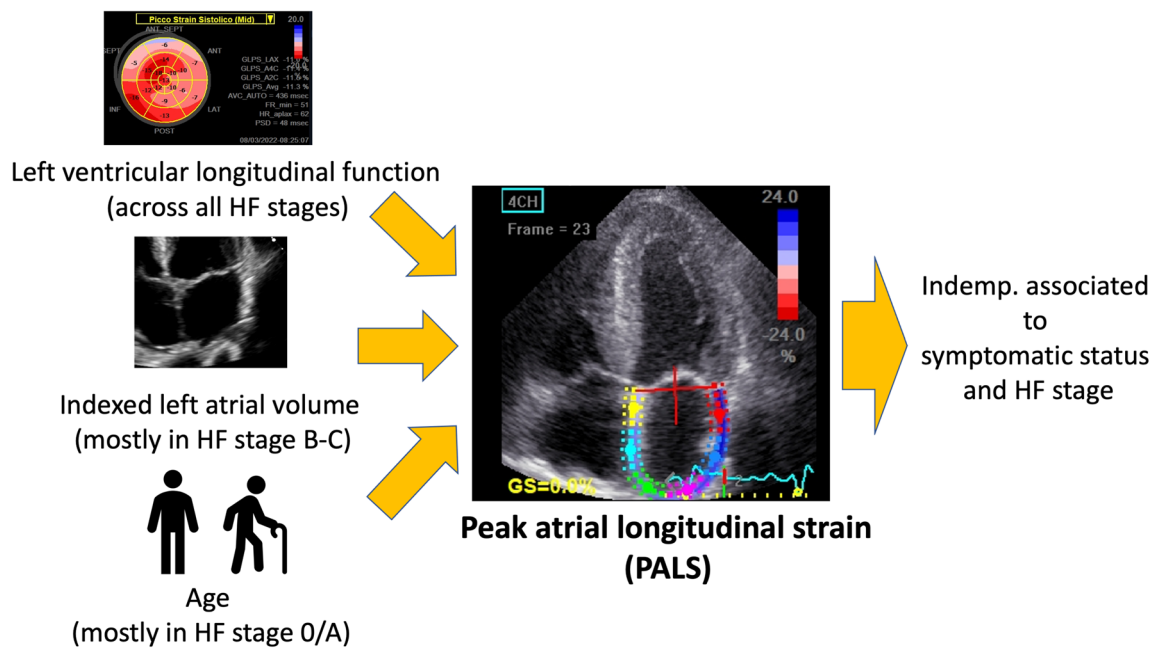


Fig. 2 The figure summarizes the most important PALS determinants

Table 2 Univariable and multivariable multiple regression model for PALS associated features in the whole cohort and according to HF-stages.

	PALS determinants		Determinants of reduced PALS (below the median cohort value)	
	Univariable Beta ± SE	Multivariable Beta ± SE	Univariable OR (95%CI)	Multivariable OR (95%CI)
Whole cohort				
Age, per 5 year	- 1.25 ± 0.11; p < 0.0001	- 0.71 ± 0.09; p < 0.0001	1.28 (1.22–1.36); p < 0.0001	1.23 (1.15–1.31); p < 0.0001
LAVI, per 3 mL/m ²	- 0.96 ± 0.07; p < 0.0001	- 0.63 ± 0.06; p < 0.0001	1.24 (1.19–1.29); p < 0.0001	1.20 (1.14–1.25) p < 0.0001
LV-GLS, per 3%	- 4.28 ± 0.23; p < 0.0001	- 3.6 ± 0.20; p < 0.0001	2.26 (1.96–2.23); p < 0.0001	2.39 (2.01–2.85) p < 0.0001
HF stage 0/A				
Age, per 5 year	- 0.95 ± 0.22; p < 0.0001	- 0.61 ± 0.20; p = 0.03	1.33 (1.18–1.51); p < 0.0001	1.29 (1.13–1.49); p = 0.0003
LAVI, per 3 mL/m ²	- 0.81 ± 0.33; p = 0.01	- 0.78 ± 0.28; p = 0.002	1.05 (0.89–1.23); p = 0.5	1.04 (0.86–1.25) p = 0.7
LV-GLS, per 3%	- 5.46 ± 0.68; p < 0.0001	- 5.01 ± 0.67; p = 0.007	3.70 (2.26–3.06); p < 0.0001	3.48 (2.07–5.85) p < 0.0001
HF stage B				
Age, per 5 year	- 0.76 ± 0.17; p < 0.0001	- 0.56 ± 0.15; p = 0.0003	1.18 (1.08–1.30) p < 0.0001	1.17 (1.06–1.30); p = 0.001
LAVI, per 3 mL/m ²	- 0.59 ± 0.11; p < 0.0001	- 0.63 ± 0.09; p < 0.0001	1.14 (1.07–1.21) p < 0.0001	1.19 (1.10–1.28) p < 0.0001
LV-GLS, per 3%	- 2.76 ± 0.37; p < 0.0001	- 3.02 ± 0.36; p < 0.0001	1.85 (1.46–2.34) p < 0.0001	2.29 (1.73–3.02) p < 0.0001
HF stage C				
Age, per 5 year	- 0.16 ± 0.20; p = 0.4	- 0.14 ± 0.15; p = 0.3	1.06 (0.95–1.17); p = 0.2	1.14 (1.01–1.29); p = 0.03
LAVI, per 3 mL/m ²	- 0.51 ± 0.08; p < 0.0001	- 0.44 ± 0.07; p < 0.0001	1.18 (1.09–1.26); p < 0.0001	1.17 (1.09–1.26) p < 0.0001
LV-GLS, per 3%	- 2.86 ± 0.27; p < 0.0001	- 2.74 ± 0.26; p < 0.0001	1.69 (1.37–2.10); p < 0.0001	1.93 (1.48–2.51) p < 0.0001

PALS is used as dependent variable in the model either as continuous variable (left part of the table) or as categorical (right part of the table)
 HF heart failure; GLS global longitudinal strain; LAVI left atrial volume index; LV left ventricular; OR odds ratio; PALS peak atrial longitudinal strain

Clinical consequences of reduced PALS

Multiple echocardiographic features characterized the HF stages (Table 1, right columns). PALS was independently associated with HF stages (<0.0001) when tested together

with its determinants. Furthermore, it was the single most powerful echocardiographic parameter in predicting the HF stage (AUC for stage B vs. 0/A = 0.81, and AUC for stage C vs. 0/A = 0.76). The PALS remains independently associated with HF stages after adjusting for ejection fraction,

Fig. 3 Scatterplot illustrating the relationship between PALS and GLS. Colors identify four patients group based on the cohort’s median PALS and GLS. The green dots (preserved PALS and reduced GLS) are by far the less represented and crowded towards the fitting line

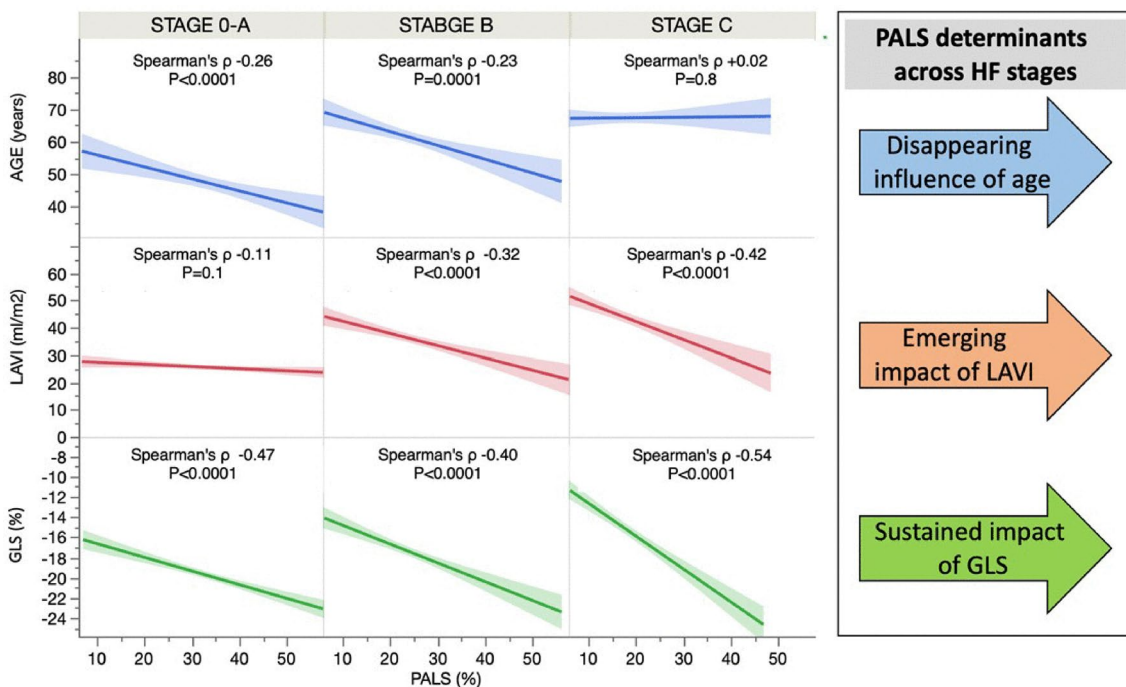
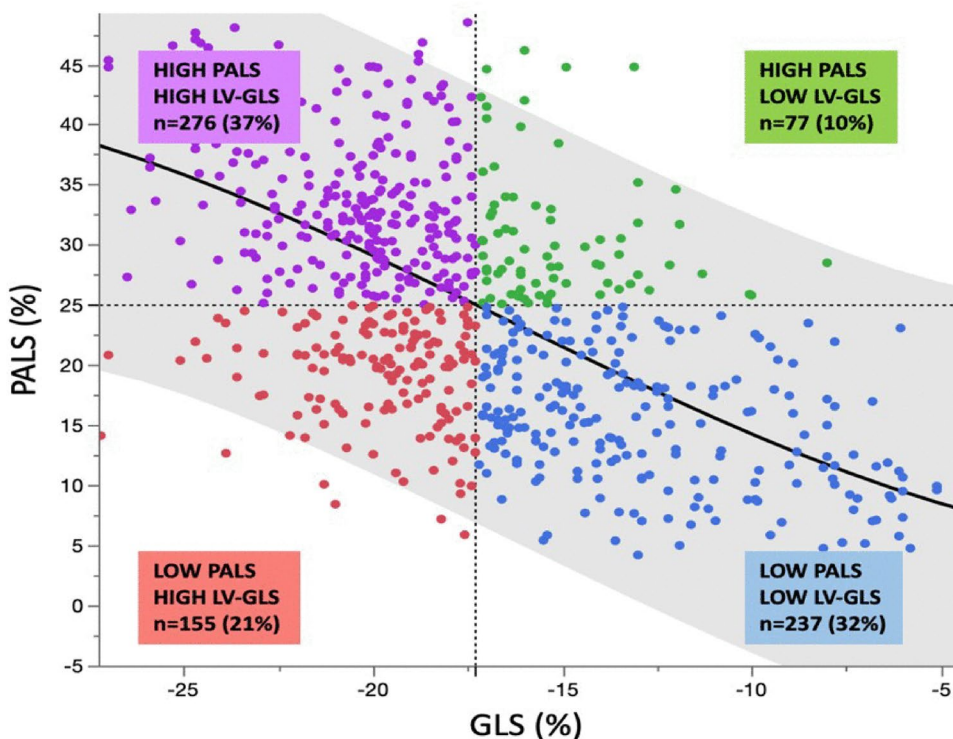


Fig. 4 Summary of the main PALS associated echocardiographic features and their interaction with H stage. Notably, as highlighted in the right panel, the age and LA volume effect on PALS is highly influ-

enced by the HF stage, whereas GLS association with PALS remains stable in all HF stage

E/e', mitral regurgitation grade ($p < 0.0001$). Results did not change, adding any of the other echocardiographic HF features (data not showed).

Figure. 5 shows the four cohort subgroups based on median PALS and GLS. There is an increasing proportion of patients with more severe HF stages moving from

patients with higher to lower PALS. Of note, reduced PALS was associated with slightly more severe HF vs. reduced GLS (middle columns).

A total of 268 (36%) patients were symptomatic (NYHA class ≥ 2) at the time of echocardiographic examination. PALS was significantly associated with symptomatic status in a multivariable model including his determinants (OR for PALS 3 unit increase 0.88 [0.81–0.96], $p=0.003$), and even after adjustment for LV ejection fraction, mitral regurgitation grade and E/e' ratio (OR for PALS 3 unit increase 0.87 [0.81–0.95], $p=0.003$).

Discussion

The present study, taking advantage of a unique large multicentric prospective cohort, demonstrates that:

- The PALS value is mostly influenced by age, LA size, and LV GLS.
- The LV GLS is the strongest determinant of PALS; of note concomitant preserved PALS and reduced LV GLS is rare.
- PALS is related to age among patients with HF stage 0/A or B, whereas the LA size is more important in more advanced HF stages (B and C).
- Despite its multiple determinants, PALS is the superior echocardiographic parameter for characterization of the HF stages and for predicting the presence of symptoms.

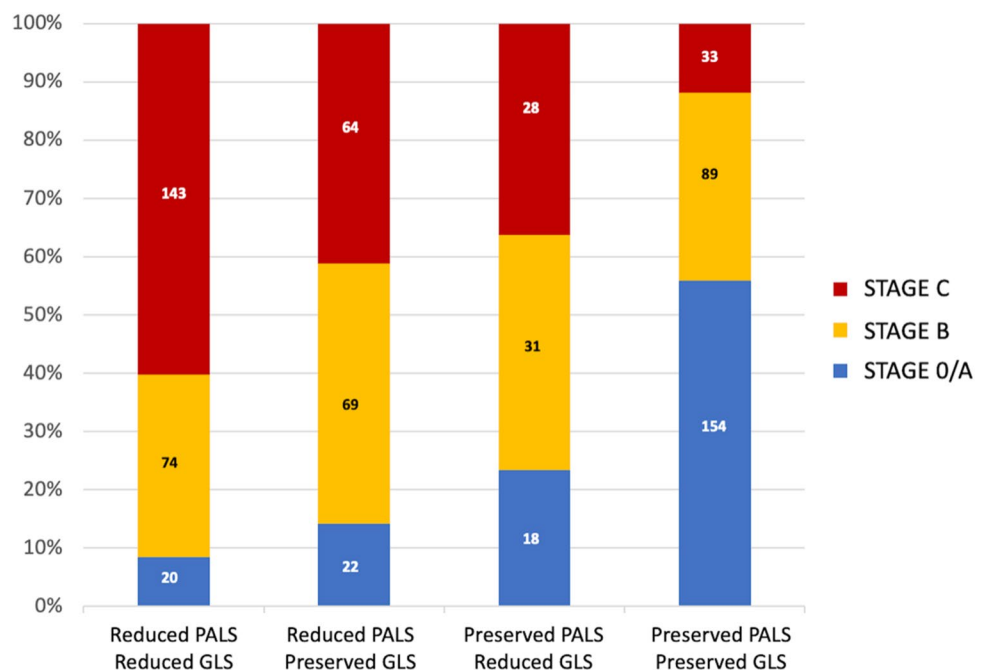
Clinical relevance of atrial function in HF

Growing evidence is accumulating on the clinical importance of the LA function—mostly measured by PALS—in all HF stages, particularly stages A and B which are characterized by early LV and LA remodeling. Indeed, LA mechanics reflect the degree of functional and morphological chamber adaptation better than the conventional echocardiographic parameters. As a paradigmatic example, patients with hypertension and diabetes have shown an early reduction of all LA myocardial deformation components even in the presence of normal LA size [18]. Furthermore, the LA function has a tight relationship with the patient clinical status, the LV filling pressure, and the pulmonary pressure [19, 20]. Lastly, the LA function has provided incremental predictive value vs. conventional parameters for almost all major HF outcomes [4, 11].

PALS and GLS across HF stages

The present study is one of the largest cohorts, specifically addressing PALS correlates, and even more important the first study to analyze differences in atrial function across multiple HF stages. There are a multitude of physiological features associated with PALS [4], but only a few are closely associated with PALS. The relationship between PALS and LV GLS has been previously reported in smaller studies conducted on healthy volunteers [6, 21], confirming the role of PALS as a marker of subclinical LV dysfunction [22]. Thus, an accumulation of evidence suggests that PALS may help identify asymptomatic patients at higher risk of

Fig. 5 Proportion of PALS/GLS grouping across HF stages. The absolute number of patients in each subgroup is reported within the columns



events in the lower HF stages. This pathophysiological role is less understood in the more advanced HF stage, where the interaction between atrial function and other hemodynamic features increases in complexity.

The present study's relatively large sample size and the wide range of explored atrial and ventricular strain values enlighten details of the PALS-GLS relationship. Indeed, the association between the two advanced echocardiographic measurements is not strictly linear, and it is rare to present with reduced GLS but preserved PALS. This aspect agrees with the potential anticipatory nature of reduced PALS towards a GLS reduction and reveals that low GLS almost invariably relates to low PALS. In other words, in patients with relatively preserved LV GLS, PALS value mostly reflects intrinsic atrial properties and holds its distinctive pathohistological role [22]; with a progressive reduction in GLS, the PALS value seems to depend more and more on LV function rather than on atrial properties.

Another novel result of the present study is that HF-stage influences the age-PALS relationship. Age seems a significant determinant of atrial stiffness in patients with no or limited cardiac involvement; however, in more advanced HF stages (B and C), different hemodynamic or biochemical drives increase LA stiffness, which becomes age-independent in HF-stage C. It is to be acknowledged that patients in HF stage B and C are older than those in stage 0/A, but the age-PALS correlation progressively decreases with the HF stage despite the similar age in stages B and C. This supports the change in determinants rather than the age ranges as a possible explanation for the significant interaction.

LA volume showed an independent association with PALS, which increased in strength moving from HF stage 0/A to C. The explanations for this behavior reside in the multiple pathophysiological meaning of LA size, which reflects the elevation of diastolic filling pressure over time [23, 24], the burden of mitral regurgitation [25], it is a sensitive morphophysiological expression of the severity of LV dysfunction, and to be a useful global index of the cardiovascular risk [26]. Despite this strong physiological background, overall, PALS values were only partially explained by the LA volume ($R=0.46$), making plausible the incremental value of the atrial function over LA size demonstrated in a variety of clinical contexts [27–29].

Limitations

The lack of follow-up is the main limitation of the study; however, the present study provides contemporary insights into PALS' clinical meaning. Indeed, this atrial parameter was the most characterizing echocardiographic parameter of HF-stage, which is mostly a clinically defined stage,

and it is not based on LA chamber characteristics or any of the PALS determinants. In invasive studies conducted in advanced HF, LA strain was the best determinant of pulmonary capillary wedge pressure among the echocardiographic features [30]. This was confirmed across patient groups with varying LV ejection fraction [31], which ultimately explains the incremental clinical value (for symptoms as well as HF stage identification) observed in our study. There is a pathophysiological explanation of this PALS clinical value over its most important determinants: the atrial function may buffer the increased ventricular filling pressure as well as volume overload due to functional mitral regurgitation, therefore being the ultimate determinant of the patients' symptomatic status [32]. This has been demonstrated for PALS in the context of mitral regurgitation [20]. Another limitation of the present study is the lack of a core lab for the assessment of echocardiographic measurements. However, no interaction between the primary regression model and centers was seen. This, together with the stable results using measurements performed by a consultant or those performed by a trainee enhance the applicability in the real world of our results.

Conclusion

In this prospective large multicenter study LV function by GLS, LA size, and age are independently associated with PALS with hierarchical importance influenced by patients' HF stage. LA strain is a crucial HF stage characterizing feature and strongly relates to the presence of symptoms.

Supplementary Information The online version contains supplementary material available at <https://doi.org/10.1007/s10554-022-02669-x>.

Author contributions Conceptualization, GB., MC., MHM., GEM., BC., TE. and BAP.; Data curation, MC., MHM., JM., GEM., GB., RA., VRL., MCP., CS., BM., DM., ED., BC., TE., and BAP.; Formal analysis, JM., GB.; Investigation, MC., MHM., JM., GEM., GB., RA., VRL., MCP., CS., BM., DM., ED., BC., TE., and BAP.; Methodology, GB., MC., MHM., JM., and GEM.; Project administration, MC.; Supervision, MC., BC., TE. and BAP.; Validation, MC., MHM., JM., GEM., GB., BC., TE., BAP.; Visualization, MC., MHM., JM., GEM., BC., TE., BAP.; Writing—original draft, GB., AM., and MC.; Writing—review & editing, MHM., JM., GEM., RA., VRL., MCP., CS., BM., DM., ED., BC., TE., and BAP All authors have read and agreed to the published version of the manuscript.

Funding Open access funding provided by Università degli Studi di Verona within the CRUI-CARE Agreement.

Data availability Data will be made available upon reasonable request.

Declarations

Conflict of interest The authors declares that they have no conflict of interest.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

1. Noue K, Khan FH, Remme EW, Ohte N, García-Izquierdo E, Chetrit M, Moñivas-Palmero V, Mingo-Santos S, Andersen ØS, Gude E, Andreassen AK, Wang TKM, Kikuchi S, Stugaard M, Ha JW, Klein AL, Nagueh SF, Smiseth OA (2022) Determinants of left atrial reservoir and pump strain and use of atrial strain for evaluation of left ventricular filling pressure. *Eur Heart J Cardiovasc Imaging* 23(1):61–70. <https://doi.org/10.1093/ehjci/jeaa415>
2. Mandoli GE, Pastore MC, Benfari G, Bisleri G, Maccherini M, Lisi G et al (2021) Left atrial strain as a pre-operative prognostic marker for patients with severe mitral regurgitation. *Int J Cardiol* 324:139–145
3. Benfari G, Noni M, Onorati F, Cerrito LF, Pernigo M, Vinco G et al (2019) Effects of aortic valve replacement on left ventricular diastolic function in patients with aortic valve stenosis. *Am J Cardiol* 124:409–415
4. Malagoli A, Rossi L, Bursi F, Zanni A, Sticozzi C, Piepoli MF et al (2019) Left atrial function predicts cardiovascular events in patients with chronic heart failure with reduced ejection fraction. *J Am Soc Echocardiogr* 32:248–256
5. Malagoli A, Rossi L, Zanni A, Sticozzi C, Piepoli MF, Benfari G (2021) Refining the role of left atrial strain in heart failure with reduced ejection fraction. *J Am Soc Echocardiogr* 34:804–805
6. Miglioranza MH, Badano LP, Mihaila S, Peluso D, Cucchini U, Soriani N et al (2016) Physiologic determinants of left atrial longitudinal strain: a two-dimensional speckle-tracking and three-dimensional echocardiographic study in healthy volunteers. *J Am Soc Echocardiogr* 29:1023–1034
7. Park JH, Kim KH, Rink L, Hornsby K, Cho JY, Cho GY et al (2020) Left atrial enlargement and its association with left atrial strain in university athletes participated in 2015 Gwangju Summer Universiade. *Eur Heart J Cardiovasc Imaging* 21:865–872
8. Pathan F, D'Elia N, Nolan MT, Marwick TH, Negishi K (2017) Normal ranges of left atrial strain by speckle-tracking echocardiography: a systematic review and meta-analysis. *J Am Soc Echocardiogr* 30:59–70
9. Tan TS, Akbulut IM, Demirtola AI, Serifler NT, Ozyuncu N, Esenboga K, Kurklu HA, Kozluca V, Ongun A, Uludag DMG, Tutar DE, Dincer I (2021) LA reservoir strain: a sensitive parameter for estimating LV filling pressure in patients with preserved EF. *Int J Cardiovasc Imaging* 37(9):2707–2716. <https://doi.org/10.1007/s10554-021-02235-x>
10. Sun BJ, Park JH, Lee M, Choi JO, Lee JH, Shin MS et al (2020) Normal reference values for left atrial strain and its determinants from a large Korean multicenter registry. *J Cardiovasc Imaging* 28:186–198
11. Benfari G, Essayagh B, Nistri S, Maalouf J, Rossi A, Thapa P et al (2021) Left atrial volumetric/mechanical coupling index: a novel predictor of outcome in heart failure with reduced ejection fraction. *Circ Cardiovasc Imaging* 14:e011608
12. Malagoli A, Rossi L, Zanni A, Sticozzi C, Piepoli MF, Benfari G (2022) Quantified mitral regurgitation and left atrial function in HFrEF: interplay and outcome implications. *Eur J Heart Fail* 24:694–702
13. Cameli M, Miglioranza MH, Magne J, Mandoli GE, Benfari G, Ancona R et al (2020) Multicentric Atrial strain comparison between two different modalities: MASCOT HIT study. *Diagnostics (Basel)* 10:946
14. Bozkurt B, Coats AJS, Tsutsui H, Abdelhamid CM, Adamopoulos S, Albert N et al (2021) Universal definition and classification of heart failure: a report of the Heart Failure Society of America, Heart Failure Association of the European Society of Cardiology, Japanese Heart Failure Society and Writing Committee of the Universal Definition of Heart Failure: Endorsed by Canadian Heart Failure Society, Heart Failure Association of India, the Cardiac Society of Australia and New Zealand, and the Chinese Heart Failure Association. *Eur J Heart Fail* 23(3):350–380
15. Lang RM, Badano LP, Mor-Avi V, Afilalo J, Armstrong A, Ernande L et al (2015) Recommendations for cardiac chamber quantification by echocardiography in adults: an update from the American Society of Echocardiography and the European Association of Cardiovascular Imaging. *Eur Heart J Cardiovasc Imaging* 16:233–270
16. Nagueh SF, Smiseth OA, Appleton CP, Byrd BF 3rd, Dokainish H, Edvardsen T et al (2016) Recommendations for the evaluation of left ventricular diastolic function by echocardiography: an update from the American Society of Echocardiography and the European Association of Cardiovascular Imaging. *Eur Heart J Cardiovasc Imaging* 17:1321–1360
17. Badano LP, Koliaas TJ, Muraru D, Abraham TP, Aurigemma G, Edvardsen T et al (2018) Standardization of left atrial, right ventricular, and right atrial deformation imaging using two-dimensional speckle tracking echocardiography: a consensus document of the EACVI/ASE/industry task force to standardize deformation imaging. *Eur Heart J Cardiovasc Imaging* 19:591–600
18. Bandera F, Mollo A, Frigelli M, Guglielmi G, Ventrella N, Pastore MC et al (2021) Cardiac imaging for the assessment of left atrial mechanics across heart failure stages. *Front Cardiovasc Med* 8:750139
19. Cerrito LF, Maffei C, Inciardi RM, Tafciu E, Benfari G, Bergamini C et al (2021) How to incorporate left atrial strain in the diagnostic algorithm of left ventricular diastolic dysfunction. *Int J Cardiovasc Imaging* 37:945–951
20. Inciardi RM, Rossi A, Bergamini C, Benfari G, Maffei C, Greco C et al (2020) Mitral regurgitation, left atrial structural and functional remodelling and the effect on pulmonary haemodynamics. *Eur J Heart Fail* 22:499–506
21. Sugimoto T, Robinet S, Dulgheru R, Bernard A, Ilardi F, Contu L et al (2018) Echocardiographic reference ranges for normal left atrial function parameters: results from the EACVI NORRE study. *Eur Heart J Cardiovasc Imaging* 19:630–638
22. Cameli M, Mandoli GE, Lisi E, Ibrahim A, Incampo E, Buccoliero G et al (2019) Left atrial, ventricular and atrio-ventricular strain in patients with subclinical heart dysfunction. *Int J Cardiovasc Imaging* 35:249–258
23. Benfari G, Miller WL, Antoine C, Rossi A, Lin G, Oh JK et al (2019) Diastolic determinants of excess mortality in heart failure with reduced ejection fraction. *JACC Heart Fail* 7:808–817
24. Hubert A, Le Rolle V, Galli E, Bidaud A, Hernandez A, Donal E (2020) New expectations for diastolic function assessment in

- transthoracic echocardiography based on a semi-automated computing of strain-volume loops. *Eur Heart J Cardiovasc Imaging* 21:1366–1371
25. Essayagh B, Antoine C, Benfari G, Messika-Zeitoun D, Michelena H, Le Tourneau T et al (2019) Prognostic implications of left atrial enlargement in degenerative mitral regurgitation. *J Am Coll Cardiol* 74:858–870
 26. Donal E, Lund LH, Oger E, Bosseau C, Reynaud A, Hage C, Drouet E, Daubert JC, Linde C (2017) KaRen investigators Importance of combined left atrial size and estimated pulmonary pressure for clinical outcome in patients presenting with heart failure with preserved ejection fraction. *Eur Heart J Cardiovasc Imaging* 18(6):629–635
 27. Pernigo M, Benfari G, Geremia G, Noni M, Borio G, Mazzali G et al (2017) Atrial function as an independent predictor of postoperative atrial fibrillation in patients undergoing aortic valve surgery for severe aortic stenosis. *J Am Soc Echocardiogr* 30:956–965
 28. Morris DA, Belyavskiy E, Aravind-Kumar R, Kropf M, Frydas A, Braunauer K et al (2018) Potential usefulness and clinical relevance of adding left atrial strain to left atrial volume index in the detection of left ventricular diastolic dysfunction. *JACC Cardiovasc Imaging* 11:1405–1415
 29. Cameli M, Sciacaluga C, Loiacono F, Simova I, Miglioranza MH, Nistor D et al (2019) The analysis of left atrial function predicts the severity of functional impairment in chronic heart failure: the FLASH multicenter study. *Int J Cardiol* 286:87–91
 30. Lundberg A, Johnson J, Hage C, Back M, Merkely B, Venkateshvaran A et al (2019) Left atrial strain improves estimation of filling pressures in heart failure: a simultaneous echocardiographic and invasive haemodynamic study. *Clin Res Cardiol* 108:703–715
 31. Cameli M, Sparla S, Losito M, Righini FM, Menci D, Lisi M et al (2016) Correlation of left atrial strain and doppler measurements with invasive measurement of left ventricular end-diastolic pressure in patients stratified for different values of ejection fraction. *Echocardiography* 33:398–405
 32. Rossi A, Dini FL, Agricola E, Faggiano P, Benfari G, Temporelli PL et al (2018) Left atrial dilatation in systolic heart failure: a marker of poor prognosis, not just a buffer between the left ventricle and pulmonary circulation. *J Echocardiogr* 16:155–161

Publisher's Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

Authors and Affiliations

Giovanni Benfari¹ · Giulia Elena Mandoli² · Julien Magne^{3,4} · Marcelo Haertel Miglioranza⁵ · Roberta Ancona⁶ · Vlatka Reskovic Luksic⁷ · Maria Concetta Pastore² · Ciro Santoro⁸ · Blazej Michalski⁹ · Alessandro Malagoli¹⁰ · Denisa Muraru¹¹ · Erwan Donal¹² · Bernard Cosyns¹³ · Thor Edvardsen^{14,15} · Bogdan Alexandru Popescu¹⁶ · Matteo Cameli² on behalf of MASCOT investigators

¹ Section of Cardiology, Department of Medicine, University of Verona, Piazzale A. Stefani 1, 37126 Verona, Italy

² Department of Medical Biotechnologies, Division of Cardiology, University of Siena, Siena, Italy

³ CHU Limoges, Hôpital Dupuytren, Service Cardiologie, 87042 Limoges, France

⁴ INSERM U1094, University of Limoges, CHU Limoges, IRD, U1094, GEIST, 2, rue Marcland, 87000 Limoges, France

⁵ Institute of Cardiology/University Foundation of Cardiology, Porto Alegre, Brazil

⁶ UOC Cardiologia/UTIC – “Santa Maria della” Grazie Hospital Pozzuoli, Pozzuoli, Italy

⁷ Department of Cardiovascular Diseases, University Hospital Centre Zagreb, Zagreb, Croatia

⁸ Department of Advanced Biomedical Sciences, Federico II, University Hospital, Naples, Italy

⁹ Department of Cardiology, Medical University of Lodz, Lodz, Poland

¹⁰ Division of Cardiology, Nephro-Cardiovascular Department, Baggiovara Hospital, University of Modena and Reggio Emilia, Modena, Italy

¹¹ Department of Medicine and Surgery, University of Milano-Bicocca, Milan, Italy

¹² University of Rennes, CHU Rennes, Inserm, LTSI – UMR 1099, 35000 Rennes, France

¹³ Centre for Cardiovascular Diseases, University Hospital of Brussels, Brussels, Belgium

¹⁴ Department of Cardiology, Center for Cardiological Innovation, Oslo University Hospital, Rikshospitalet, Oslo, Norway

¹⁵ University of Oslo, Oslo, Norway

¹⁶ Department of Cardiology, University of Medicine and Pharmacy “Carol Davila” – Eurocolab, Emergency Institute for Cardiovascular Diseases “Prof. Dr. C. C. Iliescu”, Sos. Fundeni 258, 022328 Bucharest, Romania