

Velocity vector imaging to quantify left atrial function

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Abstract The aim of our study was to assess the feasibility of a new image analysis, velocity vector imaging (VVI), in the assessment of left atrial volumes (LAV) and left atrial ejection fraction (LAEF). We retrospectively analysed 100 transthoracic echocardiographic findings in 71 men, and 29 women (mean age 57 ± 19.8 years). Two subgroups of patients were defined: (1) with left ventricular (LV) EF $> 50\%$, and (2) LV EF $< 50\%$. For the VVI method of indexed LAV assessment we used the apical four-chamber view. From the displacement of LA endocardial pixels time–volume curves were extracted which provided automatically data regarding indexed maximum LAV (LAVImax), indexed minimum LAV (LAVImin), and LAEF. LAVs and LAEF by 2-dimensional echocardiography (2DE) were measured by Simpson’s biplane disc summation method. Comparing LAVImax, LAVImin, and LAEF by VVI versus 2DE in the total study population, we found significant correlations: $r = 0.94$, $P < 0.0001$, $r = 0.94$, $P < 0.0001$, $r = 0.79$, $P < 0.0001$, respectively. In addition, LAVImax ≥ 40 ml/m² was 94% sensitive and 72% specific,

LAVImin ≥ 27 ml/m² was 90% sensitive and 86% specific, and LAEF $< 30\%$ was 80% sensitive and 96% specific for the detection of LV systolic dysfunction. There were highly significant inverse associations of LAVImax and LAVImin to LVEF. LAEF was also significantly related to LV systolic function. When comparing the time required for VVI and 2DE measurements, VVI led to 62% reduction in the measurement time. In conclusion, VVI is a feasible method for the assessment of LAVs and LAEF. It provides close agreement with that measured by conventional 2DE Simpson’s biplane method with significant time saved.

Keywords Left atrial volume · Left atrial ejection fraction · Velocity vector imaging · Left ventricular systolic function

Introduction

Left atrial (LA) size is an important predictor of cardiovascular events [1–8]. Different methods exist for the assessment of LA size [9]. The American Society of Echocardiography recommended left atrial volume (LAV) and its indexed value (LAVI) assessed by 2-dimensional echocardiography (2DE), to measure LA size [10]. We undertook this study to determine whether a novel image analysis, known as velocity vector imaging (VVI), can quantify LAV.

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Patients and methods

We retrospectively analysed 10 transthoracic echocardiographic findings recorded from January to September 2008. Standard transthoracic 2DE and Doppler examinations were performed by one echocardiographer (GV) according to the established clinical laboratory practice using Siemens Sequoia (Siemens Medical Solutions, Inc., Mountain View, California) with an ultrasound transducer operating at 4V1c or 3V2c. During the examination tissue harmonic imaging was used. The images were digitally recorded, stored on magneto-optical discs, and offline analysed. Only echocardiograms of adequate quality were considered. The only exclusion criterion was atrial fibrillation. All the measurements were based on a single measurement of one cardiac cycle. We defined two subgroups of patients: (1) with normal left ventricular (LV) ejection fraction (EF) > 50%, and (2) LV systolic dysfunction, EF < 50%. Left ventricular EF was measured using the modified biplane Simpson's rule. Echocardiographic maximum and minimum left atrial volumes indexed to body surface area (LAVImax and LAVImin) were measured by Simpson's biplane disc summation method [9]. Apical four- and two-chamber views were used at end-systole from the frame immediately preceding mitral valve opening for LAVImax measurement, and at end-diastole, the time at which atrial volume was at its nadir before mitral valve closure, for LAVImin measurement. VVI is a unique technique with complex signal processing but an easy assessment of the time-volume curves [11, 12]. It requires only a single frame tracing of the endocardial border to extract quantitative time-motion and volume data. The new software (Axius; Siemens Medical Solutions, Inc., Mountain View, California) was used for offline VVI analysis. For the VVI method of LAVI assessment we used the apical four-chamber view. The endocardium of the LA was manually traced starting from the lateral side of the mitral annulus and ending at medial side, excluding the confluence of the pulmonary veins and LA appendage (Fig. 1). We observed tracing the LA at end-systole to provide the best tracking for the cardiac cycle. The velocity vectors superimposed on the 2DE images were generated. From the displacement of LA endocardial pixels time-volume curves were extracted which provided data regarding LAVmax and LAVmin (Fig. 2). All VVI derived LAV measurements were

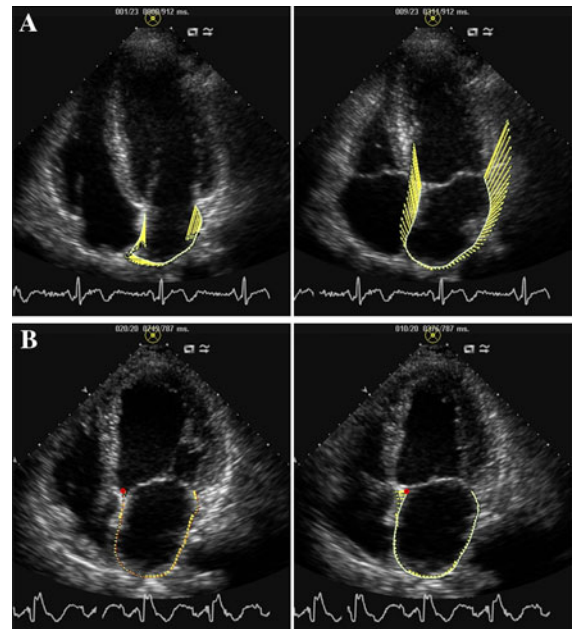


Fig. 1 Assessment of left atrial volumes by vector velocity imaging. After manual tracing of the left atrial endocardium, velocity vectors are generated in cine loop format (*left panels*—atrial end-systole, *right panels*—atrial end-diastole). **a** Patient with normal left ventricular systolic function, **b** patient with left ventricular systolic dysfunction

indexed to body surface area. Left atrial ejection fraction (LAEF) was calculated automatically by VVI method and in case of 2DE according to the formula: $LAEF = (LAV_{max} - LAV_{min}) / LAV_{max} \times 100\%$.

In 20 randomly selected patients (10 with normal EF and 10 with EF < 50%), LAVIs and LAEF by VVI method were reanalysed 1 month later in a blinded fashion for evaluation of intraobserver and interobserver variabilities. In each of these 20 patients the time required for measurements of LAVIs and LAEF by VVI and 2DE was also recorded. The beginning of the measurement was considered the moment of selection of the programme for VVI measurement and volume measurement in case of 2DE. The end of the measurement was considered the moment of acquiring the numerical data.

Statistical analysis

Data are expressed as mean \pm standard deviation. Significant differences between groups were demonstrated using paired *t* test. Differences were considered

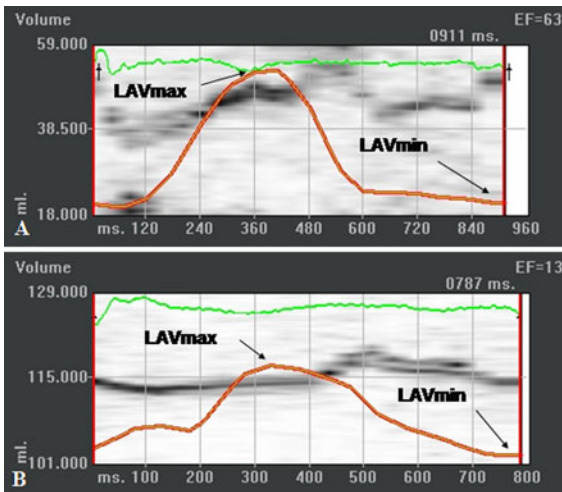


Fig. 2 Time-volume curves extracted from velocity vector imaging. **a** Patient with normal left ventricular systolic function. **b** Patient with left ventricular systolic dysfunction. *LAVmax*—left atrial maximum volume, *LAVmin*—left atrial minimum volume

statistically significant at a *P*-value of <0.05. Linear regression analysis was used to determine the correlation between LAVIs assessed by VVI and 2DE. Analysis of agreement was performed using the method proposed by Bland and Altman [13]. Limits of agreement were defined as mean ± 0.95 × SD of differences. Observer variability was also expressed in correlation coefficient and analysis of agreement. Receiver-operating characteristic curves were constructed to test the ability of LAVIs and LAEF to identify patients with LV systolic dysfunction.

Results

The study population consisted of 100 patients (71 men, 29 women, mean age 57 ± 19.8 years, range

Table 2 Left atrial volumes and ejection fraction using VVI and 2DE

	LV EF > 50%	LV EF < 50%	<i>P</i>
VVI			
LAVImax (ml/m ²)	35.13 ± 14.34	66.67 ± 19.42	<0.0001
LAVImin (ml/m ²)	17.45 ± 11.18	51.34 ± 18.98	<0.0001
LAEF (%)	52.4 ± 12.76	24.6 ± 13.96	<0.0001
2DE			
LAVImax (ml/m ²)	30.32 ± 12.92	57.54 ± 15.4	<0.0001
LAVImin (ml/m ²)	19.94 ± 10.92	48.76 ± 15.29	<0.0001
LAEF (%)	36.89 ± 11.17	16.21 ± 10.41	<0.0001

Data are expressed as mean ± SD

VVI velocity vector imaging; *LAVImax* indexed maximum left atrial volume; *LAVImin* indexed minimum left atrial volume; *LAEF* left atrial ejection fraction; *LV EF* left ventricular ejection fraction; *2DE* 2-dimensional echocardiography (assessment of the left atrial volume by Simpson’s biplane disc summation method)

17–85 years). Baseline clinical characteristics are presented in Table 1. There were highly significant differences in the measured values between the two groups of patients (Table 2).

In the whole group of patients we found an excellent correlation and agreement in LAVIs and moderate correlation in LAEF assessment between VVI and 2DE measurements (Fig. 3).

Patients with normal LVEF (>50%)

Mean LVEF was 58.82 ± 6.86%. LAVImax and LAVImin measured by VVI was 35.13 ± 14.34 ml/m², and 17.45 ± 11.18 ml/m², respectively. LAEF was 52.4 ± 12.76%. LAVImax and LAVImin measured by 2DE Simpson’s biplane method were 30.32 ± 12.92, and 19.94 ± 10.92 ml/m², respectively. LAEF by 2DE was 36.89 ± 11.17% (Table 2).

Comparing LAVIs by VVI with LAVIs assessed by 2DE, we found excellent correlations: LAVImax by VVI versus LAVImax by 2DE: *r* = 0.94,

Table 1 Baseline clinical characteristics of the total study population and patients with and without left ventricular systolic dysfunction

Variable	Total study population (n = 100)	LV EF > 50% (n = 50)	LV EF < 50% (n = 50)
Age (years)	57.07 ± 19.87	68.34 ± 12.54	45.84 ± 19.52
Men/women	63/37	23/27	40/10
Body surface area (m ²)	1.84 ± 0.19	1.84 ± 0.21	1.85 ± 0.18
Hypertension	49 (49%)	15 (30%)	34 (68%)
Diabetes mellitus	29 (29%)	6 (12%)	23 (46%)
Coronary artery disease	48 (48%)	6 (12%)	42 (84%)

Continuous data are expressed as mean ± SD

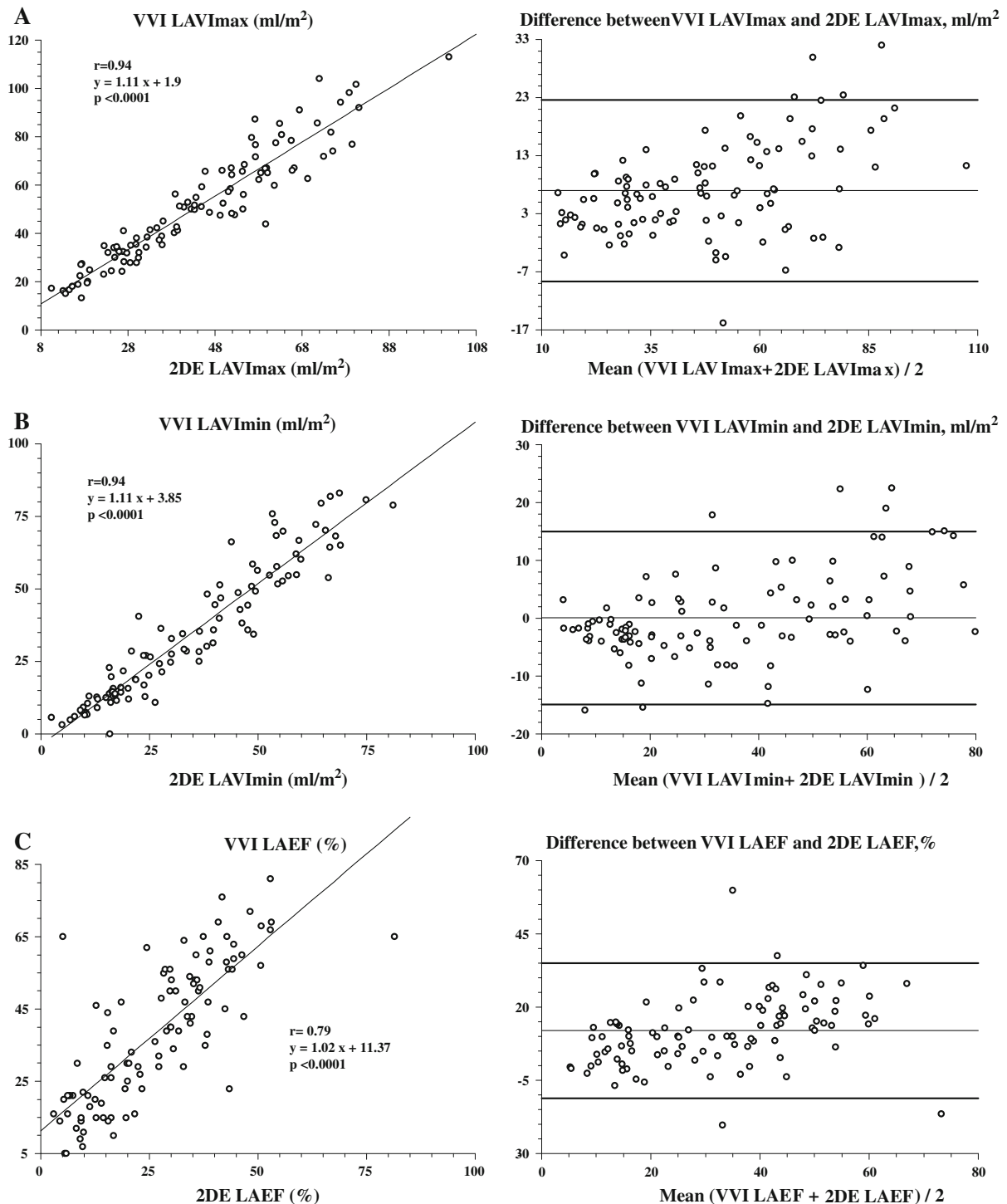


Fig. 3 The results of a linear regression analysis (left panels) and Bland–Altman plots of agreement (right panels) between indexed left atrial maximum volume (LAVImax), indexed left atrial minimum volume (LAVImin), and left atrial ejection

fraction (LAEF) (a, b, and c, respectively) measured by velocity vector imaging (VVI) and 2-dimensional echocardiography (2DE biplane Simpson’s method)

Table 3 Comparison of VVI to 2DE: regression analysis

	VVI	<i>r</i>	<i>P</i>	95% CI	Regression equation	Mean difference	Limits of agreement
Total study population							
LAVI _{max}		0.94	<0.0001	0.91–0.96	$y = 1.11x + 1.9$	6.96 ml/m ²	−8.62; 22.56
LAVI _{min}		0.94	<0.0001	0.92–0.96	$y = 1.11x + 3.85$	4.58 ml/m ²	−14.87; 14.97
LAEF		0.79	<0.0001	0.70–0.85	$y = 1.02x + 11.37$	11.94%	−11.17; 35.06
LV EF > 50%							
LAVI _{max}		0.94	<0.0001	0.90–0.96	$y = 1.04x + 3.35$	4.8 ml/m ²	−4.55; 14.16
LAVI _{min}		0.92	<0.0001	0.86–0.95	$y = 0.94x + 1.35$	−2.48 ml/m ²	−11.05; 6.09
LAEF		0.63	<0.0001	0.42–0.77	$y = 0.72x + 25.77$	15.5%	−4.82; 35.83
LV EF < 50%							
LAVI _{max}		0.86	<0.0001	0.77–0.92	$y = 1.09x + 3.75$	9.12 ml/m ²	−10.03; 28.29
LAVI _{min}		0.87	<0.0001	0.79–0.92	$y = 1.08x + 1.74$	2.57 ml/m ²	−15.48; 20.64
LAEF		0.53	<0.0001	0.30–0.70	$y = 0.71x + 12.97$	8.38%	−15.43; 32.21

The abbreviations as in Table 2

$P < 0.0001$, and LAVI_{min} by VVI versus LAVI_{min} by 2DE: $r = 0.92$, $P < 0.0001$. However, comparing LAEF by VVI versus LAEF by 2DE there was moderate correlation but still highly significant: $r = 0.63$, $P < 0.0001$ (Table 3).

Patients with left ventricular systolic dysfunction (EF < 50%)

Mean LVEF was $31.84 \pm 11.05\%$. In this group of patients we found significant correlations in LAVI and LAEF assessment, however, the values were less robust as in a group of patients with LVEF > 50%. The data are presented in Table 3.

According to agreement analysis there was systematic overestimation of LAVIs and LAEF by VVI method except of LAVI_{min} in a group of patients with normal LV function (Table 3).

Value of LAVI and LAEF for the detection of LV systolic dysfunction

We examined the sensitivity and specificity of LAVI and LAEF for the detection of systolic dysfunction at different LAVI and LAEF values to develop a receiver-operator characteristic curve. LAVI_{max} ≥ 40 ml/m² was 94% sensitive and 72% specific, LAVI_{min} ≥ 27 ml/m² was 90% sensitive and 86% specific, and LAEF < 30% was 80% sensitive and 96% specific for the detection of LV systolic

dysfunction (Fig. 4). C statistics calculated as the area under the receiver-operator characteristic curve were the same for VVI and 2DE (Table 4).

Association of LAVI and LAEF with LV systolic function

There were highly significant inverse associations of LAVI_{max} and LAVI_{min} to LVEF. LAEF was also significantly related to LV systolic function (Fig. 5).

Intraobserver and interobserver variability

The intraobserver correlation coefficient, mean differences and standard errors were: in LAVI_{max} $r = 0.97$ ($P < 0.0001$), mean difference 1.94 ± 12.58 ($P = 0.24$), standard error 2.81; in LAVI_{min} $r = 0.96$ ($P < 0.0001$), mean difference 0.51 ± 11.81 ($P = 0.42$), standard error 2.64; and in LAEF $r = 0.89$ ($P < 0.0001$), mean difference 0.15 ± 8.71 ($P = 0.46$), standard error 1.94. The interobserver correlation coefficient, mean differences and standard errors were: in LAVI_{max} $r = 0.97$ ($P < 0.0001$), mean difference 0.11 ± 5.05 ($P = 0.46$), standard error 1.12; in LAVI_{min} $r = 0.96$ ($P < 0.0001$), mean difference -0.45 ± 5.52 ($P = 0.35$), standard error 1.23; and in LAEF $r = 0.91$ ($P < 0.0001$), mean difference 1.05 ± 8.16 ($P = 0.28$) and standard error 1.82.

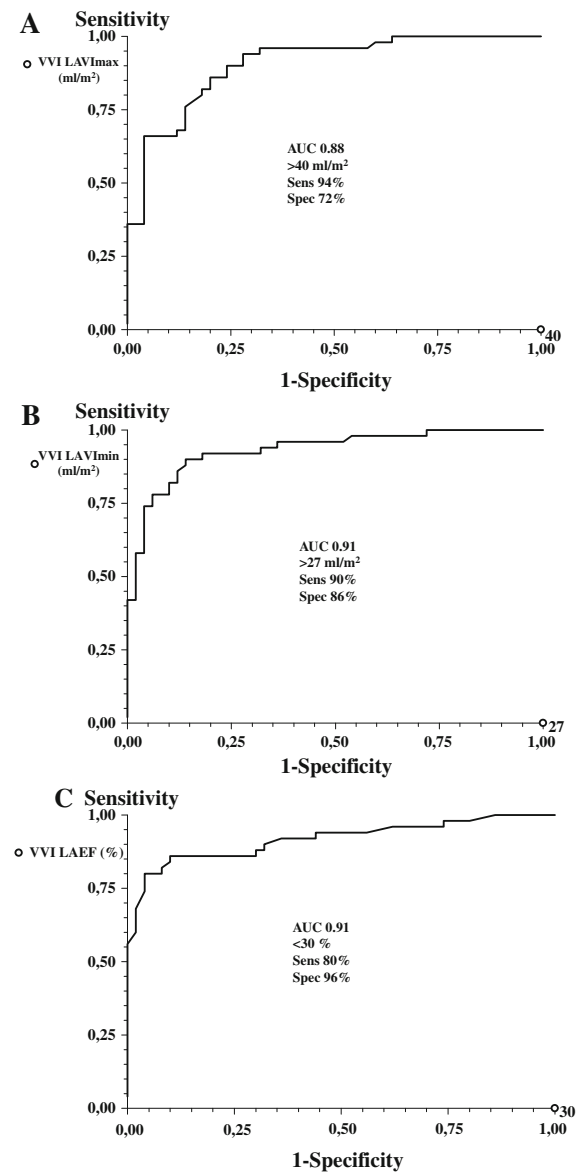


Fig. 4 Receiver-operating characteristic curves for the detection of left ventricular systolic dysfunction. Area under curve (AUC), sensitivity, and specificity for indexed left atrial maximum volume (LAVImax), indexed left atrial minimum volume (LAVImin), and left atrial ejection fraction (LAEF) (a, b, and c, respectively)

Table 4 Predictive characteristics of LAVIs and LAEF for detection of systolic dysfunction in the study population

	AUC (VVI)	AUC (2DE)	Optimum cut-off point (VVI)	Sensitivity (VVI)	Specificity (VVI)
LAVImax	0.88	0.89	40 ml/m ²	0.94	0.72
LAVImin	0.91	0.91	27 ml/m ²	0.9	0.86
LAEF	0.91	0.91	30%	0.8	0.96

AUC area under receiver-operating characteristic curve (95% confidence interval); other abbreviations as in Table 2

Time required for VVI and 2DE measurements

Mean VVI measurement time was 27.87 ± 1.09 s and mean 2DE measurement time was 73.3 ± 5.29 s. Thus, VVI led to significant 62% reduction in the measurement time by VVI in comparison with 2DE ($P < 0.0001$). However, in case of 2DE only LAVImax and LAVImin were automatically provided by the built-in calculation programme. LAEF calculation would require additional time.

Discussion

Volume of the LA is an important surrogate parameter of the heart function. While LA size assessed by a single linear measurement of the anterior-posterior diameter obtained from M-mode or 2DE has already been shown to be an independent prognostic indicator of cardiovascular events, LAV has been shown to be an even stronger predictor [14–17]. Doppler assessment of the transmitral inflow provides information related to instantaneous pressures in the LV and LA. LAV is a measure of the chronicity and severity of systolic and diastolic dysfunction and is less load dependent. It has been likened to “glycosylated hemoglobin” in the assessment of LV filling pressures.

There are different methods in the assessment of LAV using 2DE (LA planimetry, area-length method, monoplane or biplane Simpson’s method) [9]. The American Society of Echocardiography has recommended quantification of LAV by biplane transthoracic echocardiography either using the method of discs (Simpson’s rule) or the area-length method [10]. Several studies have proved that LAV assessed by three-dimensional echocardiography, which can be considered as a gold standard in the assessment of LAV, is significantly related to the methods of 2DE. Therefore, 2DE methods of LAV measurements can be used for follow-up evaluation [18–22]. One major

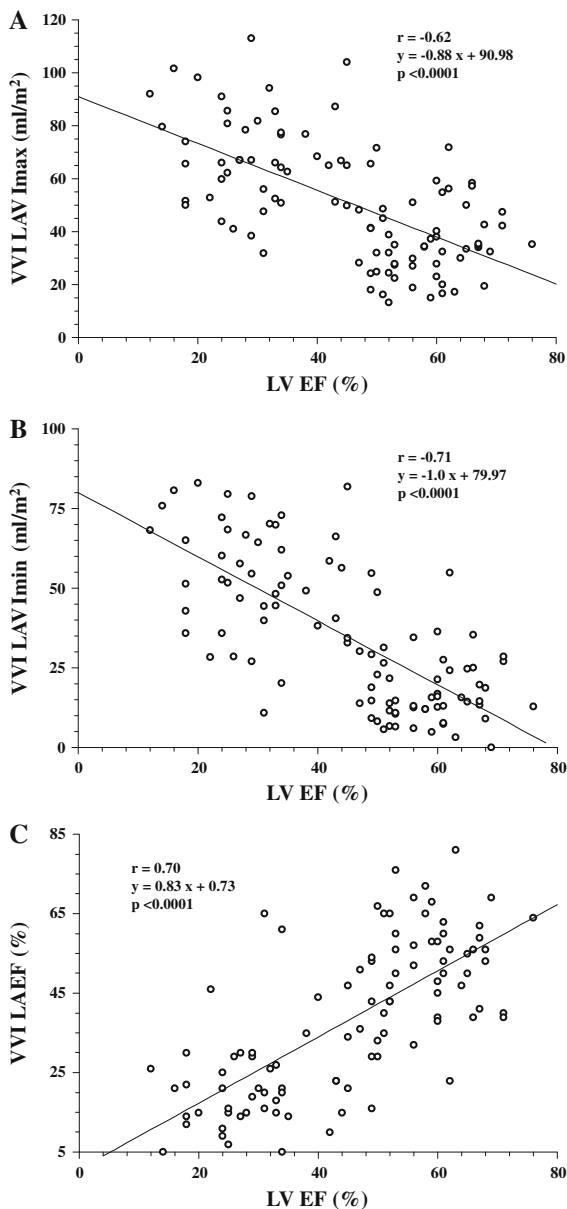


Fig. 5 Association of indexed left atrial maximum volume (LAVI_{max}), indexed left atrial minimum volume (LAVI_{min}), and left atrial ejection fraction (LAEF) with left ventricular ejection fraction (LV EF) (a, b, and c, respectively)

disadvantage is that they are time-consuming procedures not practical in daily clinical practice.

VVI is a novel quantitative echocardiographic technique which requires only a single frame tracing of the endocardial border to extract quantitative time-volume data. The major advantage of VVI is simplicity and short acquisition time. As it was presented in our

study, it provides volume data comparable with the recommended 2DE method of discs. Moreover, VVI led to 62% reduction in the measurement time in comparison with 2DE.

However, we found an excellent correlation and agreement in LAVIs between VVI and 2DE, for LAEF there was poor to moderate correlation. This may be related to the fact that LAVIs by VVI were overestimated when compared with 2DE. As LAVI_{max} was more overestimated as LAVI_{min}, this resulted in higher LAEF by VVI and so less robust correlation in LAEF by VVI versus 2DE.

In our study we also analysed the relation between LAVI and LV systolic function. LAVIs significantly increased in deteriorating LV systolic function. LAVI_{max} ≥ 40 ml/m², LAVI_{min} ≥ 27 ml/m², and LAEF $< 30\%$ were highly sensitive and specific for the detection of LVEF $< 50\%$. The value of LAVI_{max} > 40 ml/m² is concordant with the results of the study by Ristow et al. [23] who proved that this volume is predictive to mortality to similar degree as LV systolic dysfunction. Moreover, the American Society of Echocardiography recommends the same value of LAVI (>40 ml/m²) as the cutoff for “severe” LA dilatation [10]. Generally, only maximum LA size is routinely measured in clinical practice. The prognostic significance of LAVI_{min} and LAEF has not been evaluated so far. We think that LAVI_{min} and LAEF should have prognostic implication for predicting adverse events in patients with different cardiovascular disorders, analogous to LV end-systolic volume and LVEF. Further studies are needed to prove this assumption.

The major limitation of our study is that we did not use a “gold standard” method (e.g., magnetic resonance imaging, computed tomography) for validation of VVI. Another limitation is that we used VVI in the four-chamber view and compared with 2DE measurements performed in both four- and two-chamber views. The current VVI method has been designed for only single-plane analysis, although biplane or even three-dimensional analysis would be more accurate for LAV measurements.

The potential benefits of VVI reside in providing not only LAVs but also in evaluation of LA phasic function, so besides LAVI_{max} and LAVI_{min}, assessment of LA reservoir volume, conduit volume, and booster pump volume. In that regard a recent study by Ogawa et al. [24] reported that VVI can be used for

the rapid and noninvasive automated quantification of LA phasic function. However, the central hypothesis of this study was the assessment of the LA function from time-volume curves, it also demonstrated good agreement between VVI and 2DE in the measurement of LAVs, but in a considerably smaller group of individuals (10 normal subjects and 20 patients). Moreover, speckle-tracking imaging methods have a potential for the assessment of LA strain and strain rate, as it has been recently proposed by several studies [25–27].

Conclusion

VVI is a feasible method for the assessment of LAVs and LAEF. It provides close agreement with that measured by conventional 2DE Simpson's biplane method with significant time saved. This simplified technique can be readily applied in the clinical setting for reliable and quick quantification of LA enlargement.

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