Non invasive evaluation of left ventricular elastance according to pressure-volume curves modeling in arterial hypertension

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Keywords: left ventricular elastance, hypertension, three-dimensional echocardiography

DISCLOSURES:

No conflicts of interest, financial or otherwise, are declared by the authors.

Abstract:

Background- End systolic left ventricular (LV) elastance (Ees) has been previously calculated and validated invasively using LV pressure-volume (PV) loops. Non invasive methods have been proposed, but clinical application remains complex. The aim of the present study was to 1) estimate Ees according to modeling of LV PV curve during ejection ("Ejection PV Curve" method) and validate our method with existing published LV PV loops data. 2) test clinical applicability to detect non invasively a difference in Ees between normotensive and hypertensive subjects.

Methods and Results- Based on ejection PV curve and a linear relationship between elastance and time during ejection**,** we used a non linear least square method to fit the pressure waveform. We then computed slope and intercept of time varying elastance, and volume intercept V0. As a validation,–22 PV loops obtained from previous invasive studies were digitized and analyzed using the "Ejection -PV Curve" method. To test clinical applicability, ejection PV curves were obtained from 33 hypertensive and 32 normotensive subjects with carotid tonometry and real time 3D echocardiography during the same procedure. A good univariate relationship (r^2=0.92, $p<0.005$) and good limits of agreement were found between invasive calculation of Ees and our new proposed "Ejection PV Curve" method. In hypertensive patients, an increase in Ea was compensated by a parallel increase in Ees without change in Ea/Ees. In addition, the clinical reproductibility of our method was similar to that of another non invasive method.

Conclusions- Ees and V0 can be estimated non invasively from modeling of the PV curve during ejection. This approach was found to be reproducible and sensitive enough to detect an expected increase in LV contractility in hypertensive patients**.** Due to its non invasive nature, this methodology may have clinical implications in various disease states.

New & Noteworthy

The use of RT3DE-derived LV volumes in conjunction with arterial tonometry was found to be reproducible and sensitive enough to detect expected differences in LV elastance in artrial hypertension. Due to its noninvasive nature, this methodology may have clinical implications in various disease states.

Introduction

Evaluation of systolic left ventricular (LV) performance is of high importance in physiological investigation and clinical practice. An ideal parameter of LV contractility should assess inotropic state independently of preload, afterload, heart rate, and LV remodeling. This assessment still remains somewhat elusive, but parameters derived from LV pressure and volume have become the gold standard to achieve it (4). The relationship between LV end-systolic pressure and volume from a variably loaded cardiac contraction yields the end-systolic pressure-volume (PV) relationship, its slope and intercept being end-systolic elastance (Ees) and the hypothetical volume at zero pressure (V0), respectively (Figure 1 A). Ees is a parameter of LV contractility, but it is also influenced by chamber geometry and passive myocardial stiffening (4,7).

Ees normally matches with vascular load in order to achieve near optimal mechanical function. Combined analysis of arterial elastance (Ea) and Ees expressed as the ratio-Ea/Ees is a marker of LV-arterial coupling. In healthy persons, Ea and Ees are close with an optimal function range of Ea/Ees between 0.6 and 1 (4). Age associated arterial stiffening (5) and hypertension (2) are matched with LV systolic stiffening, with a concordant increase in Ees and Ea. Antihypertensive therapy reduces both Ea and Ees and enhances LV-arterial coupling (15). Afterload mismatch occurs when Ees falls and/or Ea rises, resulting in an increase in Ea/Ees corresponding to a reduced LV performance and efficiency. In 466 patients with heart failure, Ea/Ees was a potent predictor of death and need for cardiac transplantation. In addition, the intercept V0 of the end-systolic PV relationship was associated with prognosis in chronic heart failure (14).

In the past, Ees and V0 were calculated according to invasive LV PV measurements obtained under a wide range of loading conditions, thus limiting the clinical applicability of

this technique. To avoid these limitations, several methods (invasive and more recently non invasive) have been proposed to estimate Ees from an averaged single cardiac cycle (25-6). Despite the additional novel aspects of these methods, clinical application remains questionable mainly because of numerous assumptions, such as the use of an average normalized LV elastance curve (6-29).

It is now well established that real time 3D echocardiography (RT3DE) allows more accurate quantification of LV volume than 2D echocardiography (15). Commercially available echographs give access to 3D LV volume raw data. Using RT3DE LV volume and carotid pressure curves obtained from tonometry during LV ejection, it is possible to reconstruct non-invasively part of the real time PV relationship.

In the present study, we tested this approach, using calculation of Ees and V0 based on analysis and modeling of non invasive LV PV curve during ejection. First, in order to demonstrate the feasibility and accuracy of our "Ejection PV Curve" method, we compared estimated Ees with invasively determined Ees from previous studies. Second, we assessed the clinical applicability of our method to detect differences in Ees between normotensive and hypertensive subjects.

METHODS

1-Theoretical framework and validation against published LV PV loop data

Theoretical considerations for Ees and V0 estimation:

It has been shown that LV time-varying elastance during systole could be represented by two linear functions, one for the isovolumic contraction phase and the other for the ejection phase (Figure 1 B). In anesthetized dogs, increase in LV elastance during ejection was predominantly constant and non linearity accounted for only 2% of the variance (27). According to this observation, LV elastance during ejection can be expressed as:

$$E(t) = \frac{p(t)}{v(t) - V0} = a * t + b \quad [1]$$

Wherein (i) p(t) is time-varying pressure, (ii) v(t) is time-varying volume, (iii) V0 is the intercept of end systolic PV ratio and a and b are respectively the slope and intercept of time-varying elastance curve. From [1], p(t) during ejection can be expressed as a non linear function of parameters a, b and V0:

$$p(t) = (a * t * v(t)) + (b * v(t)) - (a * t * V0) - (b * V0) \quad [2]$$

According to measured pressure and volume waveforms, a non linear least squares method is used to compute parameters a, b and V0 (20). Knowing a and b and using [1], Ees is estimated as E(t) at the end of ejection.

Validation with invasive PV loop from the literature

The hemodynamic parameters of our model ("Ejection PV Curve" method) were numerically adjusted to match 22 invasive PV loops from 7 clinical and 15 animal experimental studies. In these invasive investigations, real-time pressure was measured using a micro manometer, and volume was assessed using the conductance method. Conventional determination of end-systolic PV relationship from multiple PV loops was performed at varying preload and Ees was calculated as the slope of this end systolic PV relationship. (1,3,6,10,18,11,19,21,23,24, 26,28,31-34).

Data analysis

Published PV loops were digitized using Qcad software (RibbonSoft, *www.ribbonsoft.fr*). The ejection portion of PV loops was used to get p(t) and v(t) (see Figure 2). Because the time variable cannot be extracted from PV loops, we assumed that the relationship between LV volume and time was linear during the mid-systole. This was indeed the case in the 32 normotensive subjects of the following clinical study (data not shown). With v(t) and p(t), we were able to fit equation [2] and to compute Ees as described above.

2-Clinical study

Study design.

The goal of this non invasive study was to determine whether the "Ejection PV Curve" method is sensitive enough to detect difference in Ees. For this, we compared normotensive volunteers and patients with treated essential hypertension in a cross-sectional study. In addition, our technique was compared to the non invasive estimation of Ees according to the method developed by Chen et al (6).

Participants.

The study population (normotensive and hypertensive subjects) consisted in 65 subjects (34 males and 31 females) aged 20 to 70 years (median 40 years) recruited from the outpatient clinic of the Department of Medicine and Hypertension in Montpellier, France. Patients were investigated for cardiovascular evaluation. Hypertension was present in 33 subjects (19 males and 14 females) and all of them were receiving antihypertensive treatment**.** Patients with clinical evidence of atherosclerosis (stroke, coronary and peripheral artery disease), heart failure, renal failure (serum creatinine higher than 130 μmol/l), diabetes mellitus (fasting blood glucose > 6.7 mmol/l), marked obesity (body mass index ≥ 35 kg/m^2), a history of alcohol abuse (more than 5 drinks per day) and secondary hypertension were excluded. In order to minimize the influence of physical activity on LV mass, athletes (defined as a daily duration of physical activity of 1 hour or more) were not included. Doppler echocardiography was used to eliminate valvular lesions in all patients. The protocol was approved by the Institutional Review Board, and each subject provided informed consent.

Data acquisition.

-LV volume quantification by echocardiography: Patients were imaged by the same observer (GDC) in a supine position with the use of a SC2000 (Siemens) ultrasound system

(Siemens, Mountain View, CA). A 2.5-4.5 MHz transducer and a 4Z1c transducer were used for two and three dimensional (2D and RT3DE) imaging, respectively. Three dimensional image acquisition was performed using a wide-angle "full-volume" mode, in which the operator focused primarily on including the entire LV within the pyramidal data set. Measurements were done according to the recommendations of American and European Society of Echocardiography (16).

To ensure reasonably accurate identification of end-systolic volume, the temporal resolution of RT3DE imaging was maximized without compromising spatial resolution. Only patients with high quality imaging were included. As the maximal temporal resolution was only 20 volumes /sec (mean 14±4 volumes/s) and, as the real end-diastolic and end-systolic volumes may be missed in case of high heart rates, only patients with resting heart rate <80b/min were included. The studies were stored digitally for subsequent analysis.

-LV morphology and LV ejection time measurements: M-mode Echocardiographic assessment of LV morphology and Doppler measurement of LV Ejection time were performed during the same procedure. Interventricular septal and posterior wall thickness at end-diastole were measured according to the "Penn" convention. Relative wall thickness at end-diastole was calculated as the ratio of twice the posterior wall thickness to left ventricular end-diastolic internal diameter. LV mass was calculated by the Penn-cube method. Technical details were reported elsewhere (8).

-Central blood pressure recording: According to recommendations (17), carotid artery applanation tonometry was recorded using the SphygmoCor system (AtCor Medical, Sidney, Australia).

Tonometric and echographic PV curve analysis:

RT3DE was analyzed off-line using a commercial software (Siemens Syngo SC2000

workplace), which was used to automatically track the endocardial boundary in 3D space throughout the cardiac cycle and generate a time varying curve of LV volume (Figure 3). Thereafter, end-systolic (ESV) and end-diastolic (EDV) LV volumes were obtained and stroke volume (SV) and ejection fraction (EF) were calculated as EDV-ESV and SV/EDV, respectively. The calibrated carotid artery applanation tonometry time varying pressure was used to estimate central aortic waveform. As shown in Figure 3, LV ESP was estimated from the dicrotic notch of time varying pressure (22)**.**

Carotid pressure and LV volume from 3 consecutive cardiac cycles were averaged and synchronized using the onset of LV ejection as the time reference.

Estimation of Ees and Ea:

Ees was estimated using our new proposed "Ejection PV Curve" method (see study 1) but also with the method proposed by Chen et al (6). To compute Ees, the end of ejection was located at the dicrotic notch of pressure recording. According to Sunagawa et al (30), Ea was calculated as the ratio of ESP to SV.

Intra observer reproducibility analysis:

In order to assess the reproducibility, PV curve acquisition and measurements were repeated by the same observer one week later in 10 of the 33 hypertensive subjects.

Statistical analysis:

SPSS software (SPSS Inc., Chicago, IL) was used for statistical analysis. In the theorical study, linear regression analysis was performed to determine the correlation between estimated Ees using the "Ejection PV Curve" method and invasively measured Ees. In addition, the limits of agreement (defined as ±2 SDs from the mean difference) between the 2 methods were determined using Bland-Altman analysis. In the clinical study, differences in continuous variables between normotensive and hypertensive subjects were assessed by the

Student t-test for parametric data and differences in categorical data were assessed by the chi-square analysis. The relationships between Ea, Ees, Ea/Ees and potential predictors (clinical parameters and LV morphology) were first examined using linear univariate regression analysis. Variables that exhibited significant univariate correlation were then included in a linear multivariate regression analysis. Intra observer reproducibility was determined by the coefficient of variation.

Unless otherwise stated, results are expressed as mean ± standard deviation (SD) or median (interquartile range). Statistical significance was set at $p < 0.05$.

RESULTS:

1-Theoreticaly Study

As shown in Figure 4, a wide range (1.12-12.9 mmHg/ml) of Ees was obtained. Univariate relationship between estimated Ees by the "Ejection PV Curve" method and invasively measured Ees was highly significant (r^2=0.92, $p<0.005$). The range of 95% limits of agreement between both methods for Ees calculation was ±1.71 mmHg/ml.

Based on data from one sample PV loop with an estimated Ees at 3.9 mmHg/mL, we performed a sensitivity analysis to detect the respective influence of 10% variation in time and volume. The calculated averaged Ees (with standard deviation) were 3.0±1.2 and 3.8±0.5 mmHg/mL for time and volume variations, respectively (data not shown).

2-Clinical Study:

-LV-arterial coupling in normotensive and hypertensive subjects

As detailed in Table 1, hypertensive patients had significantly higher blood pressure (BP) than normotensive subjects (137/80 vs 117/68 mm Hg, respectively, $p< 0.01$). No difference in mean age, body mass index, sex ratio or heart rate was detected between hypertensive and

normotensive subjects. LV mass index and relative wall thickness were significantly higher in hypertensive than in normotensive subjects. Despite similar LV EDV and ESV in both groups, V0 was significantly higher in hypertensive than in normotensive subjects.

As shown in Figure 5, Ees and Ea were significantly higher in the hypertensive group than in the normotensive group but mean Ea/Ees ratio was similar.

In the entire population, the main correlates of Ea were age, systolic BP and RWT (see Table 2). However, in multivariate analysis, only systolic BP was independently and positively correlated with Ea. Age, gender and systolic BP were positively correlated to Ees. We did not find any relationship between left ventricular geometry (LVM or RWT) and Ees (data not shown). In multivariate analysis, the relationship with Ees remained significant only for male gender and systolic BP. Ea/Ees was positively correlated with male gender and RWT, the later being the only significant correlate of Ea/Ees in multivariate analysis.

-*Comparison of* "Ejection PV Curve" *method with "Chen" method:*

As shown in Figure 6, in the entire population, a strong relationship was found between Ees estimated by "Ejection PV Curve" and Chen methods (r^2 =0.96, $p<0.005$). The range of 95% limits of agreement between both methods for Ees calculation was ±0.95 mmHg/ml.

-*Intra observer reproducibility*

The results of the reproducibility analysis are summarized in Table 3. Intra-observer variability of Ees expressed in 10 hypertensive subjects was good, as reflected by a coefficient of variation of 12 and 14 % for "Ejection PV Curve" and Chen methods, respectively.

DISCUSSION:

In the present study, a non invasive method was developed to estimate Ees. Based on a linear relationship between elastance and time during ejection, Ees was calculated and validated by

comparison with invasive measurements from previous published studies. A good relationship was found between the two methods. In addition, the clinical reproducibility of the "Ejection PV Curve" method was similar to that of another non invasive method developed by Chen et al (6). In our study, Ees evaluation with the "Ejection PV Curve" method was sensitive enough to detect a significant difference in Ees between hypertensive and normotensive subjects. In agreement with previous studies, it was confirmed that the increase in Ea associated with hypertension is compensated by a parallel increase in Ees, without change in LV-arterial coupling.

PV loop acquisition and analysis:

A theoretical advantage of this novel approach, the so called "Ejection PV Curve" method, is the possibility to assess non-invasively the ejection phase of PV loop. PV curve was obtained with two non invasive well validated methods: RT3DE for LV volume and applanation tonometry for central BP. A firmly established superiority of 3D imaging over cross-sectional slices of the heart is the improvement in the accuracy of the evaluation of LV volume by eliminating the need for geometric modeling. The validity of RT3DE imaging for LV volume acquisition has been demonstrated by multiple studies comparing RT3DE volume measurements with widely accepted reference techniques, including radionuclide ventriculography and cardiac magnetic resonance (16). The RT3DE approach showed a higher level of agreement with the respective reference technique than with the conventional 2DE methodology. Additionally, RT3DE measurements were found to be more reproducible than 2DE (16). In the present study, reproducibility of volume curve during ejection was excellent with a mean coefficient of variability of 10 and 14 % for LV EDV and ESV, respectively (table 3).

Central aortic pressure was estimated by non invasive recording of the calibrated carotid artery pressure waveform using a micromanometer-tipped probe by the technique of

applanation tonometry. This method has been validated vs invasive measurements in 18 subjects undergoing cardiac catheterization by Kelly et al (12), who found that invasive and non invasive tonometry carotid pressures were highly correlated ($r=0.96$, $p<0001$). In addition, no significant difference in central systolic BP was detected. Carotid artery waveform recorded by applanation tonometry were similar in contour to those recorded with intra-aortic high fidelity catheter tip manometers (12).

Because RT3DE and tonometry cannot be performed simultaneously, it remains necessary to use an averaged pressure cycle vs an averaged LV volume cycle, instead of instantaneous pressure vs instantaneous volume. Thus, the fitted portion of the PV loop here reflects a global performance cycle and does not take into account an exact punctual correspondence between individual volume and pressure measurements. Moreover the time synchronization between the volume and pressure cycle in this study was done, based on linear interpolation on the pressure signal.

Ees estimation:

One additional novel aspect of our study was the use of an alternative technique to calculate LV elastance. Most non invasive and validated methods previously used to assess LV elastance are based on different algorithms which include multiple measured and estimated parameters**.** In the method developed by Chen et al (6), in addition to ESP and LV volume measurements, the algorithm needs LV pre-ejection time measured by aortic and mitral Doppler flow. In addition, this complex method includes an estimated and average normalized LV elastance at end diastole, calculated from invasive measurements in 18 patients. In order to simplify this technique, Gayat et al (9) proposed an alternative approach based on Shishido work (27). They included an indirect estimation of LV end-diastolic pressure using the Doppler diastolic pulmonary venous flow deceleration time. Despite this simplification, these techniques remain complex with a high risk of error. Our “Ejection PV Curve” method to

estimate Ees is based only on the analysis of a portion of PV loop without any others measurements than pressure and volume. We use the non linear least squares methods to obtain slope and intercept of time varying elastance, but also volume intercept V0. Then Ees is estimated according to E(t) at the end of ejection. This procedure is easy, and not time consuming. In addition, according to the large availability and simplification of software, pressure and volume signals synchronization is now easily accessible.

Hypertension , LV remodeling and Ees:

In order to reduce potential confounding factors, we recruted a highly selected population with controlled hypertension. Our results suggest that Ea and Ees were increased to the same proportion in hypertensive and normotensive subjects, meaning that left arterial-ventricular coupling (Ea/Ees) was similar in both groups. Our results are in accordance with the study of Borlaug et al which found that, in a large cohort of hypertensive patients, increased Ees was associated with enhanced myocardial contractility (2). However, in our study, we cannot conclude if increased Ees in hypertensive patients was the result of an increase of LV contractility or stiffness. In the same way, Lam et al found in 523 participants that antihypertensive therapy reduced arterial and ventricular stiffness, enhances ventricular–arterial coupling, reduced cardiac work, and improved LV efficiency, and systolic function (15).

One limitation of the present study is the interpretation of Ea which is highly dependent of systolic BP. The variability of this parameter according to systolic BP may explain differences in Ea/Ees between studies in hypertensive patients without same levels of BP despite similar levels of Ees (13).

Another potential limitation of this new method is the absence of a complete pressure-volume loop to evaluate stroke work or diastolic LV function.

In conclusion, Ees can be reasonably estimated from modeling of pressure and volume curves during ejection. The simplicity of our method for Ees estimation is particularly appealing. The use of RT3DE-derived LV volumes, in conjunction with arterial tonometry, to noninvasively quantify Ees was found to be reproducible and sensitive enough to detect expected differences in LV elastance. Due to its noninvasive nature, this methodology may have clinical implications in various disease states.

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LEGEND TO FIGURES

Figure 1: **Bilinearity of left ventricular elastance**

A: Schematic LV pressure-volume loop. The end-systolic pressure-volume relationship is characterized by its slope (end-systolic elastance = Ees), and a volume intercept V0. *E(t) is* instantaneous elastance. **B**: Representative *E(t)* curve (solid line) and approximation by 2 linear functions (isovolumic contraction phase and ejection phase; dashed lines) (according to Shichido et al (27)). PEP, pre-ejection period and ET, ejection time.

Figure 2: Modeling of left ventricular (LV) elastance

Schematic LV pressure-volume loop. The bold curve is converted into numerical series of individual LV pressure and LV volume data points. The least squares algorithm to fit LV pressure-volume curve during 80% of ejection time, centered on the middle of ejection (bold curve) was performed using Levenberg-Marquardt's method. ESP, end systolic pressure; EDP, end diastolic pressure; ESV, end systolic volume and EDV, end diastolic volume.

Figure 3: Pressure and volume synchronization

Sequential acquisition of real time 3D echographic left ventricular volume (top) and central aortic pressure using tonometry (bottom). The cursor signal end diastolic (EDP), end systolic (ESP) pressure and end diastolic (EDV), end systolic (ESV) volume.

Figure 4: **Correlation between "Ejection Pressure-Volume curve" and invasive methods**

Plot showing univariate relationship between end-systolic elastance estimated by "Ejection Pressure-Volume Curve" (E.P-V.C) method and invasive method (A). Corresponding Bland and Altman plot of inter-method agreement (B). The plot shows the mean difference (solid line) and the limits of agreement (dashed lines).

Figure 5: **Left ventricular-arterial coupling parameters in normotensive and hypertensive subjects**

Arterial elastance (Ea), left ventricular end systolic elastance (Ees) and Ea/Ees in 32 normotensive (NT) and in 33 hypertensive (HT) subjects (mean ±SD).

Figure 6. Correlation between "Ejection Pressure-Volume curve" and Chen's methods

Relationship between LV end systolic elastance (Ees) estimated non invasively by "Chen" and "Ejection Pressure-Volume Curve" (E.P-V.C) methods (A). Corresponding Bland-Altman plot of inter-method agreement (B). The plot shows the mean difference (solid line) and the limits of agreement (dashed lines).

Table 1. Clinical and echographic data of normotensive and hypertensive subjects

	Normotensives	**Hypertensives**	**p value***
n	32	33	
Age (years)	51.4 ± 14	56.3 ± 8	0.10
Gender (Male/Female)	15/17	19/14	0.38
Body mass index (kg/m^2)	28 ± 4.4	27 ±3.6	0.52
Systolic blood pressure (mmHg)	117 ± 15	136.7± 12	**0.0001**
Diastolic blood pressure (mmHg)	68.3 ± 9	80.4 ± 8.5	**0.0001**
Heart Rate (bpm)	70 ± 10	72 ± 8	0.69
End systolic pressure (mmHg)	96±15	111 ± 11	**0.0001**
LV mass (g)	175±35	201±56	**0.04**
Relative wall thickness	0.40±0.08	0.47±0.08	**0.04**
LV end diastolic volume (ml/m2)	61± 13	61± 12	0.64
LV end systolic volume (ml/m2)	25.1 ± 7	26.5 ± 7	0.43
LV ejection fraction (%)	60 ±6	58±6	0.31
LV volume at pressure=0 (V0) (ml)	-4.5 ± 18	1.3± 14	0.21

Values are expressed as mean ± SD. * t-test hypertensives vs normotensives. LV : left ventricular

Table 2:

Univariate relationship and multivariate analysis between clinical parameters and left ventricular morphology as independent variables, and arterial elastance (Ea), left ventricular end systolic elastance (Ees) and Ea/Ees as dependent variables.

	Univariate Relationship	**Multivariate Analysis**			
Dependent variable	**r**	**Beta**	**SE**	**t value**	**p value**
Ea mmHg/ml					
Male gender	-0.10				
Age (years)	0.48*	0.23	0.05	1.54	0.49
Systolic blood pressure (mmHg)	0.51*	0.01	0.004	3.2	**0.002**
Left ventricular mass index g/m2	0.08				
Relative wall thickness	0.33*	0.09	0.09	0.7	0.31
Ees mmHg/ml					
Male gender	-0.31*	-0.21	0.21	-1.8	**0.04**
Age (years)	0.31*	0.11	0.009	0.77	0.85
Systolic blood pressure (mmHg)	0.38*	0.02	0.008	2.6	**0.01**
Left ventricular mass index (g/m2)	-0.13				
Relative wall thickness	0.01				
Ea/Ees					
Male gender	0.21*	0.2	0.05	1.48	0.09
Age (years)	0.18				
Systolic blood pressure (mmHg)	0.02				
Left ventricular mass index (g/m2)	0.03				
Relative wall thickness	0.39*	0.4	0.30	2.8	**0.001**

*$p<0.05$

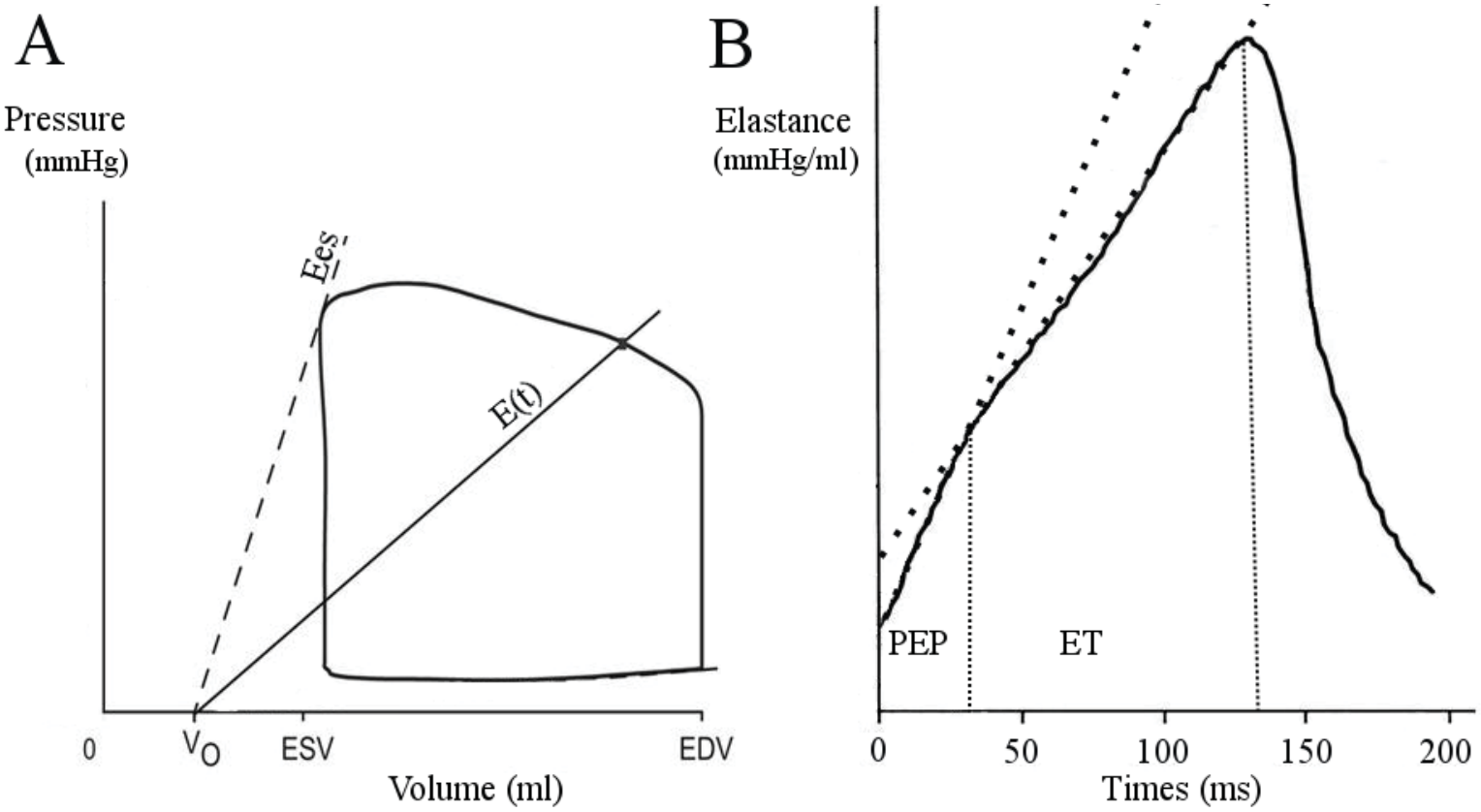
NS, no significant

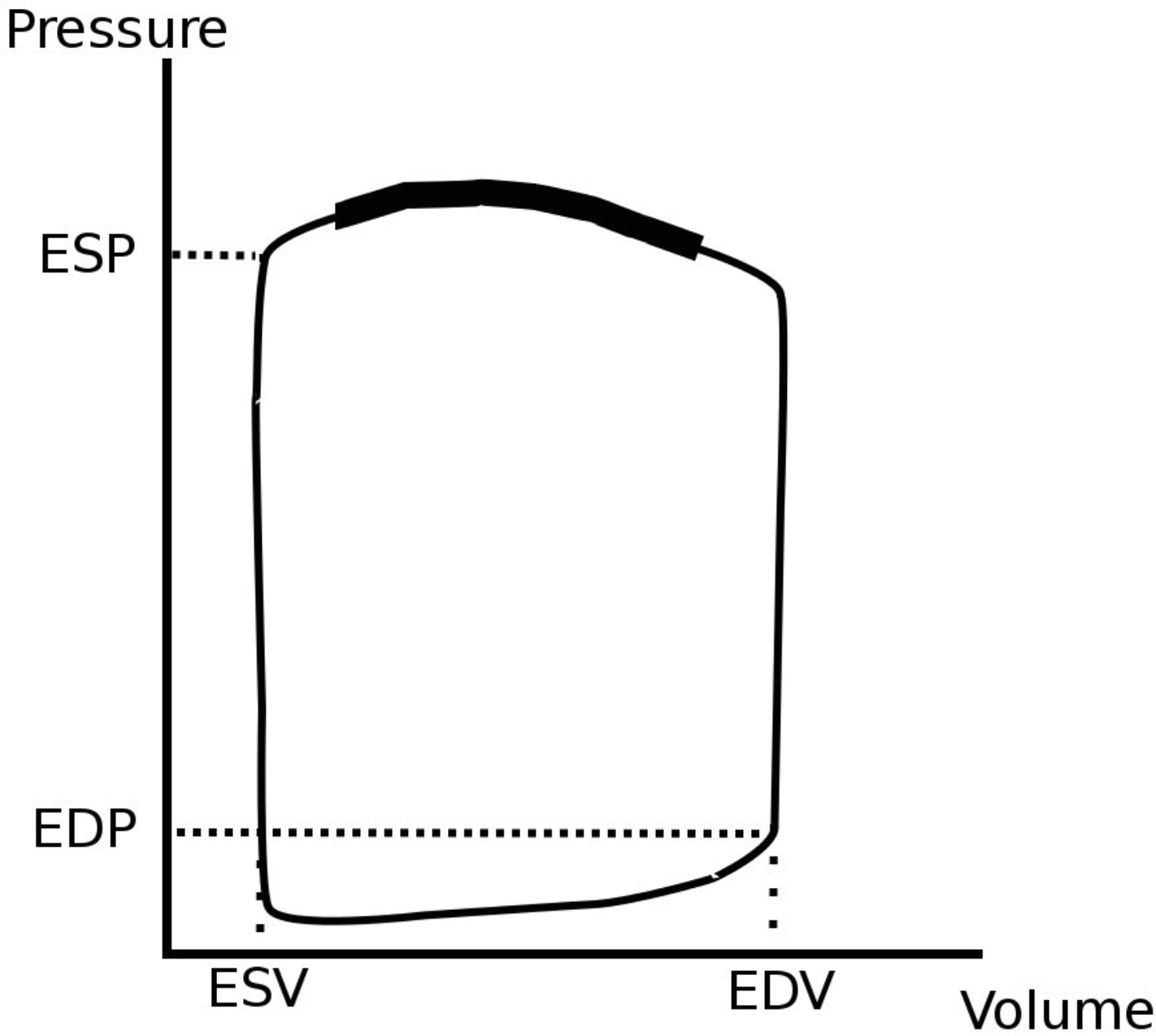
Table 3:

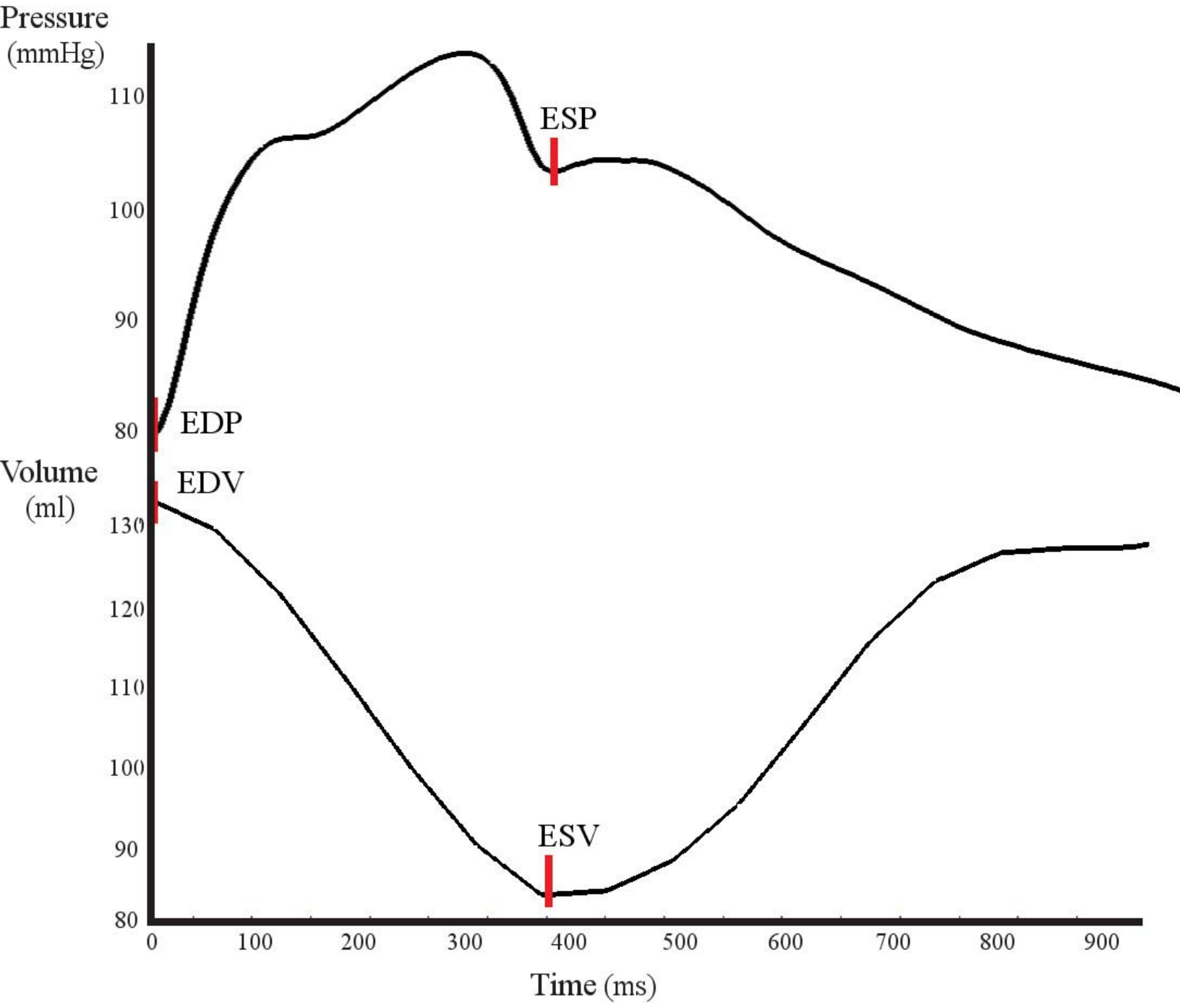
Intra-observer reproducibility of measured and calculated parameters. Left ventricular end systolic elastance (Ees) was calculated according Chen and «Ejection Pressure-Volume Curve" methods.

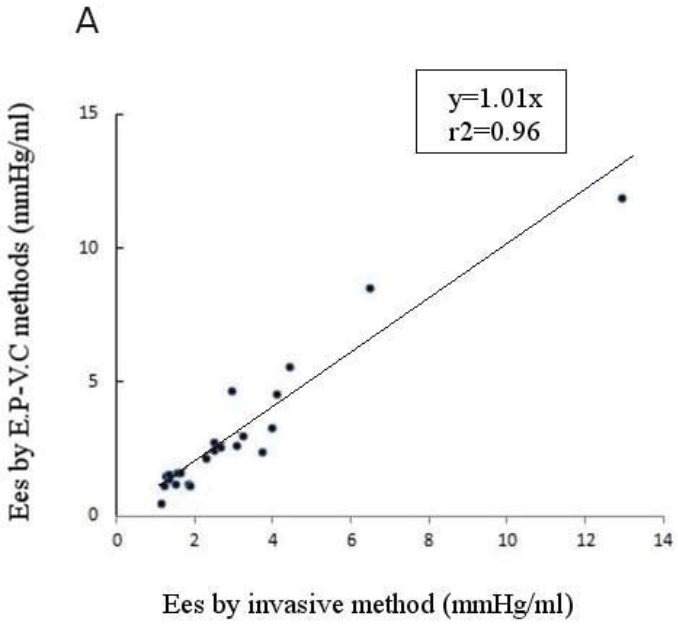
	CV (%)
LV isovolumic contraction time (ms)	10±12
LV ejection time (ms)	6±4
LV end diastolic volumes (ml)	10±9
LV end systolic volume (ml)	14±13
Ea ; arterial elastance (ml/mmHg)	17±14
Ees ; Chen method :	
Ees (ml/mmHg)	14±6
Ees ; «Ejection PV Curve" method :	
Ees (ml/mmHg)	12±6

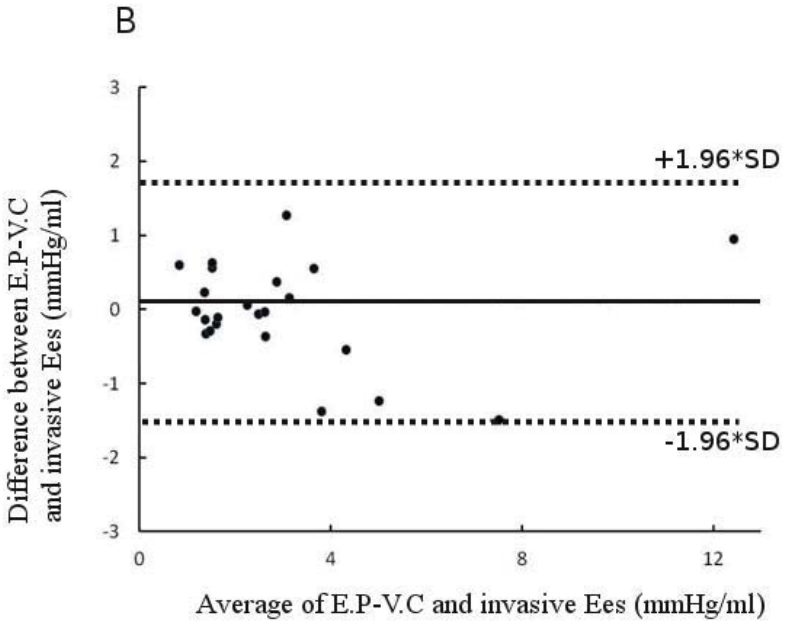
LV, left ventricular; CV, coefficient of variation (mean± standard deviation); Ea, arterial elastance.

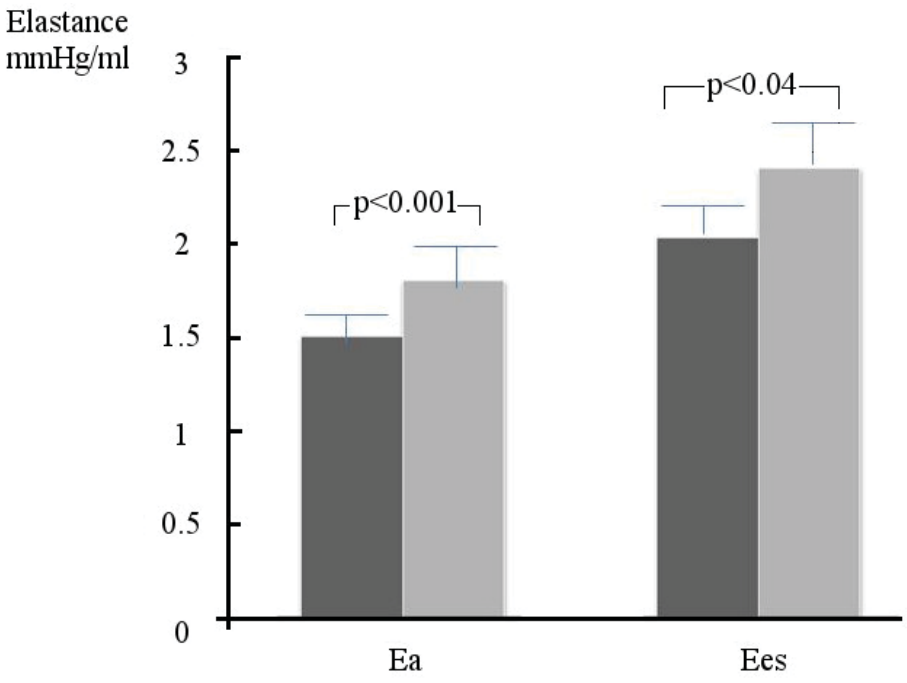

A
Pressure
(mmHg)
Ees
E(t)
0
V_O
ESV
EDV
Volume (ml)
B
Elastance
(mmHg/ml)
PEP
ET
0
50
100
150
200
Times (ms)

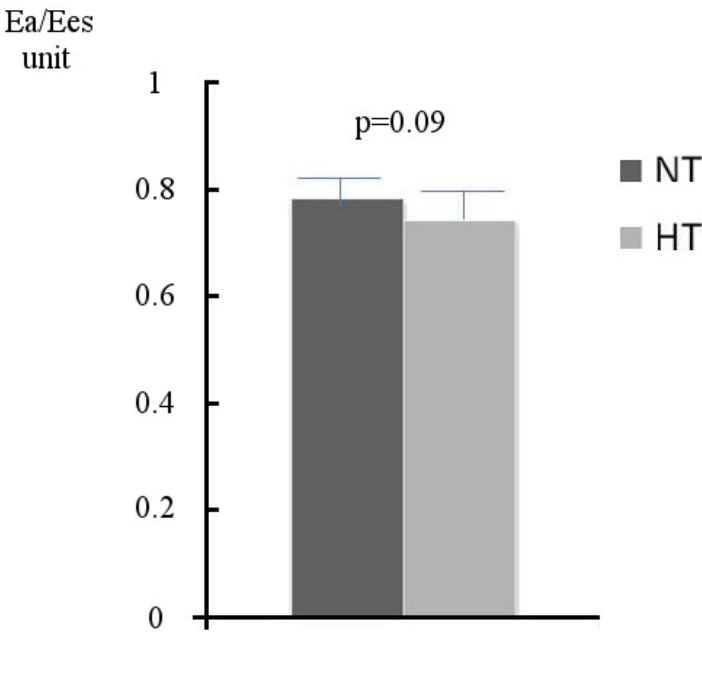

Pressure
ESP
EDP
ESV
EDV
Volume

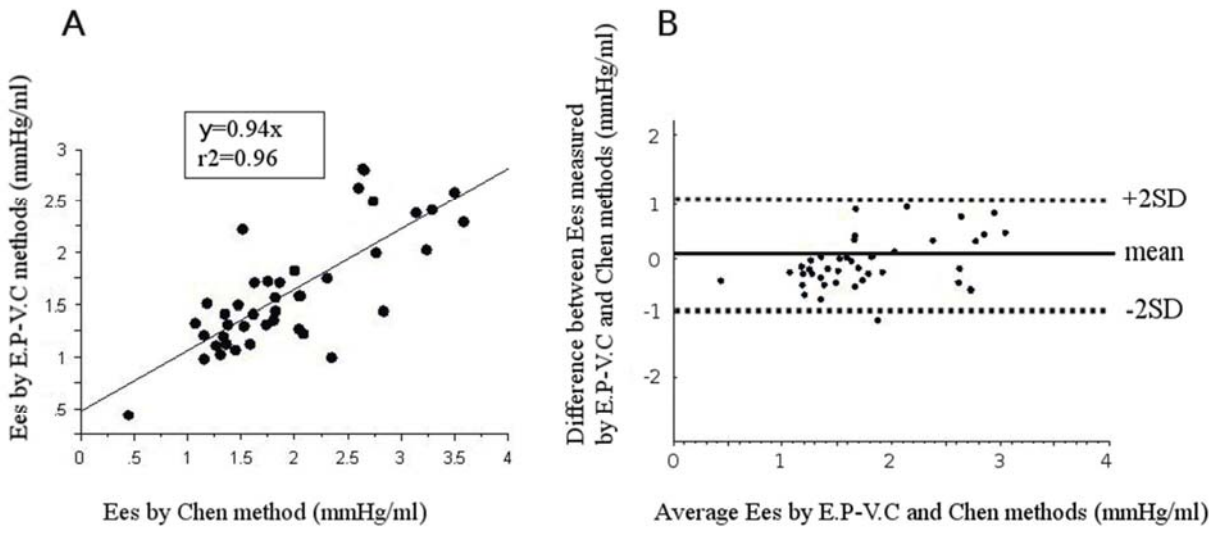

Pressure
(mmHg)
110
100
90
80
ESP
EDP
Volume
(ml)
EDV
130
120
110
100
90
80
ESV
0
100
200
300
400
500
600
700
800
900
Time (ms)


A
y=1.01x
r2=0.96
Ees by E.P-V.C methods (mmHg/ml)
Ees by invasive method (mmHg/ml)
0
5
10
15
0
2
4
6
8
10
12
14


B
+1.96*SD
-1.96*SD
Difference between E.P-V.C and invasive Ees (mmHg/ml)
Average of E.P-V.C and invasive Ees (mmHg/ml)
3
2
1
0
-1
-2
-3
0
4
8
12


Elastance
mmHg/ml
3
2.5
2
1.5
1
0.5
0
p<0.001
p<0.04
Ea
Ees


Ea/Ees
unit
1
0.8
0.6
0.4
0.2
0
p=0.09
NT
HT


A
y=0.94x
r2=0.96
Ees by E.P-V.C methods (mmHg/ml)
Ees by Chen method (mmHg/ml)
B
Difference between Ees measured by E.P-V.C and Chen methods (mmHg/ml)
+2SD
mean
-2SD
Average Ees by E.P-V.C and Chen methods (mmHg/ml)