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Assessment of Left Atrial Operative Mean Stiffness Using Simultaneous Recordings of Left Ventricular Pressure and M-Mode Echocardiography of the Left Atrium and Mitral Valve

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Abstract

Left atrial (LA) operative mean stiffness was measured using simultaneous recordings of the left ventricular (LV) pressure and M-mode echocardiography of the LA and mitral valve. The LA operative passive mean stiffness value was obtained during LV systole using LV pressure at the mitral valve opening and the pre-atrial contraction where the LV and LA pressure curves cross each other. Before the LA stiffness measurement, the LA volume calculated by biplane left atriography was compared with the dimension of the LA M-mode echocardiogram at three points (maximum volume, pre-atrial contraction and minimum volume) in another 23 patients (5 normal subjects, 4 patients with angina pectoris, 14 patients with myocardial infarction), and the regression equation was obtained by power fitting ($y=ax^3+b$). Using this equation, the LA volumes were calculated and used for the measurement of LA operative mean stiffness.

Eleven normal subjects (C group), 14 patients with myocardial infarction (ejection fraction: EF≥55%; NF group), and 12 patients with myocardial infarction (EF<55%; F group) were studied. The measured operative mean stiffness values based on the LA dimension and LV pressure [K(D)] were 0.69±0.40, 1.0±0.37, and 2.0±0.61 mmHg/mm, respectively ($p<0.01$ in C vs F and NF vs F). The mean stiffness values calculated with LA volume [K(V)] were 0.48±0.23, 0.42±0.19, and 0.66±0.25 mmHg/m*l*, respectively ($p<0.05$ in NF vs F). In F group, both the K(D) and K(V) values were high. The K(D) value can thus be used clinically as an easily obtained index of the LA operative mean stiffness. The high LA operative mean stiffness in F group appeared to be related to the increased LA pressure at the mitral valve opening.

This method of measurement of the LA operative mean stiffness can be easily applied and used as a routine measurement providing additional information regarding left ventricular function.

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Key Words

Echocardiography (transthoracic), Myocardial infarction, Atrial function, Heart catheterization

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Selected abbreviations and acronyms

C = normal subjects
EF = ejection fraction
F = failing patients with myocardial infarction (EF < 55%)
K(D) = mean left atrial stiffness calculated by left atrial dimension
K(V) = mean left atrial stiffness calculated by left atrial volume
LA = left atrium
LAD_{max} = maximum left atrial dimension
LAD_{pre-a} = left atrial dimension at pre-atrial contraction
LAP = left atrial pressure
LVP = left ventricular pressure
LAP_{mvo} = left atrial pressure at mitral valve opening
LAP_{pre-a} = left atrial pressure at pre-atrial contraction
LVP_{pre-a} = left ventricular pressure at pre-atrial contraction
NF = non-failing patients with myocardial infarction (EF ≥ 55%)
LVP_{mvo} = left ventricular pressure at mitral valve opening

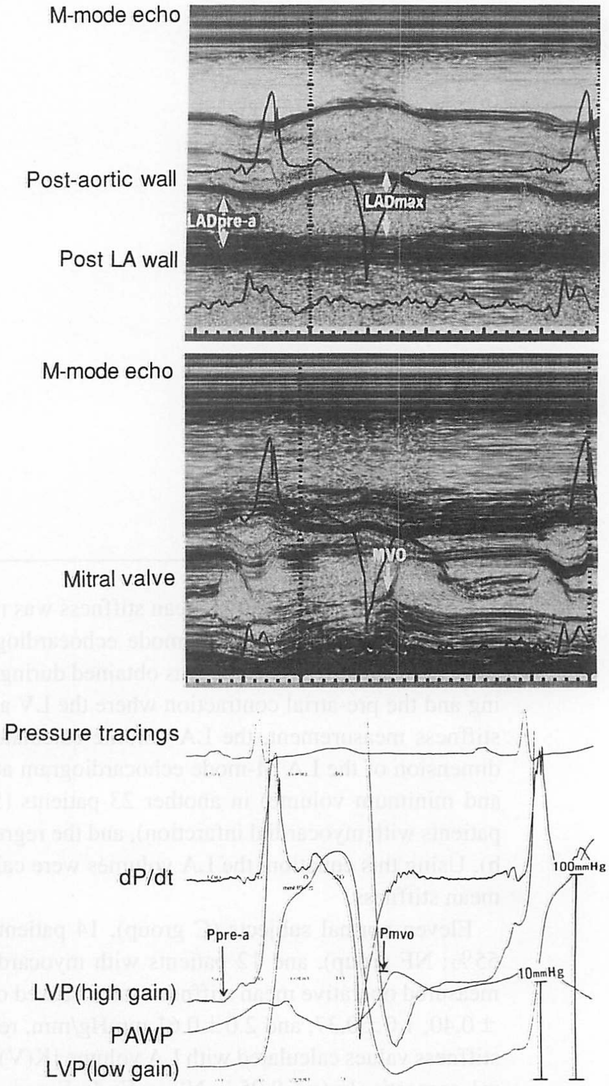

Fig. 1 Representative simultaneous M-mode echocardiograms and left ventricular pressure (LVP) tracings. Case : A 67-year-old man

The pressure at the mitral valve opening (MVO) was determined by simultaneous M-mode echocardiography of the mitral valve and recording of the LVP (*middle and lower panel*). The pressure at the pre-atrial contraction was determined from the pressure tracing just before the A wave was recorded, and the left atrial dimension at the pre-atrial contraction was determined at this point (*upper and lower panel*). PAWP = pulmonary artery wedge pressure.

INTRODUCTION

The left atrium (LA) supports the filling of the left ventricle. The stiffness of the LA influences left ventricular (LV) filling and pump performance[1–5]. This supportive function of the LA in various heart diseases[6–9], and the relationship between LA pressure and volume have been studied[10–15]. The evaluation of LA function is very important for the assessment of left ventricular (LV) function, but the measurement of LA pressure is difficult in routine cardiac catheterization. We examined a new method of assessing LA operative mean stiffness using simultaneous recording of LV pressure and the M-mode echocardiography of the LA and mitral valve.

METHODS

We studied a total of 37 patients, consisting of 11 with normal findings of heart function (C group), 14 patients with myocardial infarction (ejection fraction : EF≥55%; NF group), and 12 patients with myocardial infarction (EF<55%; F group). Informed consent was given by all patients before the study. The data of biplane left atriography in another 23 cases (5 normal subjects, 4 patients with angina pectoris, 14 patients with myocardial infarction) were utilized to obtain the relationship to the echocardiographic data.

B-mode guided M-mode echocardiography of the LA and mitral valve (Hewlett Packard 77020AC, 2.5 MHz, Wilmington, DE, USA) was recorded simultaneously with LV pressure (catheter tip manometer, Model 811-300S, Sentron, Holland) at a paper speed of 100 mm/sec (**Fig. 1**). The LA operative mean stiffness values were obtained from these data as shown in **Fig. 2**.

Measurement of LA operative mean stiffness

In the LA pressure volume loop (**Fig. 2**), the LA fills from the minimal volume to the maximum volume (from A to C). LA passive filling begins at A,

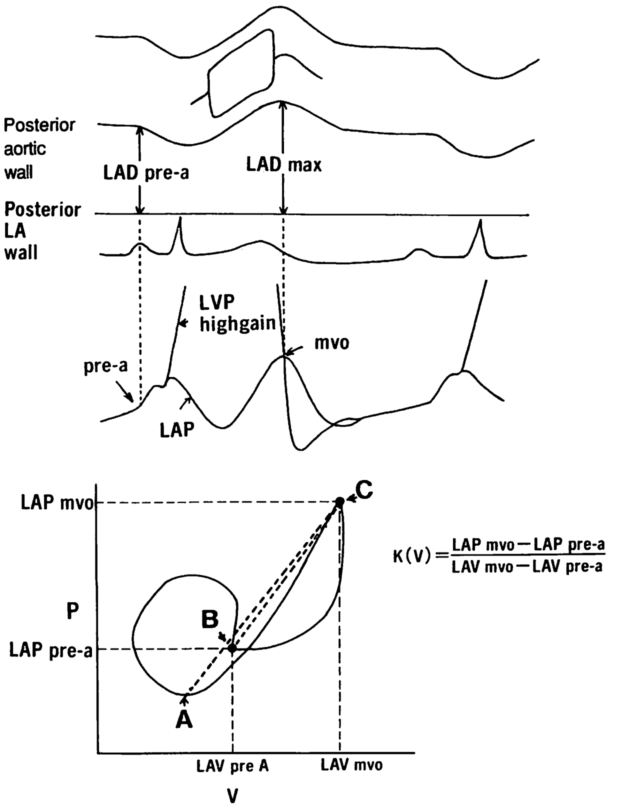

Fig. 2 Schematics of M-mode echocardiograms and left ventricular pressure tracing (*upper*) and left atrial pressure-volume loops (*lower*)

Passive filling begins at point A and ends at point C. The mean operative stiffness [K(V)] value was obtained from

$K(V) = (LAP_{mvo} - LAP_{pre\text{-}a})/(LAV_{mvo} - LAV_{pre\text{-}a})$

This equation represents the slope of the line from B to C. The actual mean stiffness is the slope of the line from A to C. At mitral valve closure, the volume of the left atrium at the pre-atrial contraction (B) is near the curve of line A to C. Thus we substituted the slope of the line B to C for that of the line A to C in this study.

Abbreviation as in Fig. 1.

and thus the slope of the line from A to C represents the mean stiffness of the LA. The LA and LV pressure curves cross at two points. One is at LV mitral valve opening; this point corresponds to point C in the LA pressure volume loop (**Fig. 2**).

LAP_{mvo} = LV pressure at mitral valve opening (LVP_{mvo})……(1)

The other point is at LA contraction; this point corresponds to point B in the LA pressure volume loop (**Fig. 2**).

$LAP_{pre\text{-}a}$ = LV pressure at pre-atrial contraction ($LVP_{pre\text{-}a}$)……(2)

Thus we can obtain the LA pressure values at these two points from the LV pressure data. As described above, the slope of the line from A to C represents the actual operative mean stiffness of the LA. However, empirically, point B is always located close to the line from A to C, so we approximated the slope from A to C using the slope of the line from B to C. Thus the slope of the line from B to C represents the mean passive stiffness of the left atrium in our method.

$$K(V) = (LAP_{mvo} - LAP_{pre\text{-}a})/(LAV_{mvo} - LAV_{pre\text{-}a})$$

The LV pressure at mitral valve opening (LVP_{mvo}) was obtained from the simultaneous M-mode echocardiograms of the mitral valve and recordings of LV pressure (**Figs. 1, 2**). The LV pressure at pre-atrial contraction ($LVP_{pre\text{-}a}$) was obtained from the recording of the LV pressure just before the atrial contraction wave (**Figs. 1, 2**). The LA dimension (LAD_{max} and $LAD_{pre\text{-}a}$) was obtained from the simultaneously recorded M-mode echocardiogram of the LA (**Figs. 1, 2**). The LA operative mean stiffness using the LA dimension [K(D)] was calculated as follows :

$$K(D) = (LAP_{mvo} - LAP_{pre\text{-}a})/LAD_{max} - LAD_{pre\text{-}a})$$

Using the equations (1) and (2), we can obtain K(D) as follows :

$$K(D) = (LVP_{mvo} - LVP_{pre\text{-}a})/(LAD_{max} - LAD_{pre\text{-}a})$$

Three consecutive beats were analyzed in each patient and averaged.

Measurement of LA volume

The LA volume was calculated by biplane left atriography in referable 23 patients, and the LA dimension obtained by M-mode echocardiography at the three points (maximum volume, pre-atrial contraction and minimum volume) were compared. The regression equation for LA dimension and LA volume obtained from biplane left atriography and LA M-mode echocardiography in the 23 patients (69 points) was $y = 0.7x^3 + 22$ ($r = 0.84$, $p < 0.05$; **Fig. 3**). In the following LA stiffness study, the LA volume was obtained using this equation in each of the 37 patients of this study. Using this equation, the LA volumes of the 37 patients in this study were calculated based on the LA dimension obtained by LA M-mode echocardiography, and were used for the measurement of LA operative mean stiffness. The LA operative mean stiffness using the LA volume [K(V)] was calculated as follows :

$$K(V) = (LAP_{mvo} - LAP_{pre\text{-}a})/LAV_{max} - LAV_{pre\text{-}a})$$

where LAV_{mvo} is the LA volume at mitral valve opening, and LAV_{pre-a} is the LA volume at pre-atrial contraction. Using equations (1) and (2), K(V) was calculated as follows :

$$K(V)=(LVP_{mvo}-LVP_{pre-a})/(LAV_{max}-LAV_{pre-a}).$$

Statistical methods

Data are expressed as mean±standard deviation. The differences in parameters between the groups were compared using Student's unpaired *t*-test, and $p<0.05$ was considered significant.

RESULTS

LA dimension, volume, and pressure

The maximum LA dimension (LAD_{max}) in the F group was significantly greater than those in the C group and NF group (both, $p<0.05$; **Table 1**). A significant difference between the F group and the other two groups was also seen for maximum LA volume calculated using the regression equation. The LA pressure at the mitral valve opening (LVP_{mvo}), and the pre-atrial contraction (LVP_{pre-a}) in the F group were significantly greater than those in the other two groups, as were the LA dimension at pre-atrial contraction and the LAD_{max}.

Pressure-dimension plots at mitral valve opening and pre-atrial contraction

The F group had a pressure-dimension plot shifted to the right and upward compared with the normal group and NF group (**Fig. 4–upper**). The pressure-volume plot of the F group was also shifted rightward and upward compared with the C group and NF group (**Fig. 4–lower**).

LA operative mean stiffness

The operative mean stiffness values calculated from the LA dimension (mmHg/mm) were 0.69±0.40 in the C group, 1.0±0.37 in the NF group, and 2.0±0.61 in the F group ($p<0.01$ in C vs F and NF vs F; **Fig. 5**). The operative mean stiffness values calculated from the LA volume (mmHg/m*l*) were 0.48±0.23, 0.42±0.19 and 0.66±0.25, respectively ($p<0.05$ in NF vs F; **Fig. 6**). Thus, in the F group, the LA operative mean stiffness was significantly increased. The increase of LA stiffness appeared to be related to the increased LA pressure at the mitral valve opening.

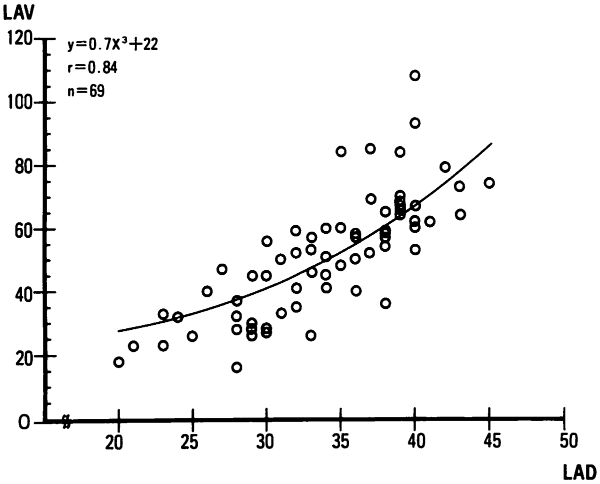

Fig. 3 Graph showing the correlation between left atrial dimension (LAD) measured by M-mode echocardiography and left atrial volume (LAV) measured by left atriography in 23 patients (69 points)
The correlation equation was $y=0.7x^3+22$, $r=0.84$, $p<0.05$.

DISCUSSION

The measurement of LA pressure is often difficult and time-consuming in routine catheterization, and the pressure is sometimes hard to record clearly because of the influence of the patient's breathing. This new method of measurement of LA stiffness is superior in that the LA pressure can be measured easily from the LV pressure. Our results indicate that in patients with low LVEF, the operative mean stiffness of the LA is increased.

LA dimension, volume, and pressure

Previous measurements of LA size using angiocardiography[16], M-mode echocardiography[17–20], and B-mode echocardiography[21,22] have indicated that patients with LA volume overload can be differentiated from those with normal LA volume. In this study, we found that the LA maximum and pre-atrial contraction dimensions were increased significantly in patients with LV dysfunction. These results are almost the same as those obtained previously[8,9], although the increase of maximum LA volume in the patients with myocardial infarction was not significant in previous studies.

LA volume calculation by M-mode echocardiography has been reported previously[18–20]. The regression equation found for the relationship between the LA volume measured by angiocardiography and the LA dimension measured by echocardiography was somewhat different from

Table 1 Left atrial dimension, volume and pressure

	LADmax (mm)	LADpre-a (mm)	LAVmax (ml)	LAVpre-a (ml)	LVPmvo (mmHg)	LVPpre-a (mmHg)
C	28.6±4.6	23.7±4.8	39.6±8.3	32.3±5.8	9.0±1.7	6.0±1.6
NF	35.6±4.6※	31.6±4.1※	55.1±13.4※	45.2±9.4※	10.0±3.3	6.1±2.6
F	39.4±3.2*†	36.0±3.1*†	65.6±10.3*†	55.4±8.4*†	13.4±3.9*†	7.0±3.3*†

*$p<0.05$ vs C, †$p<0.05$ vs NF, ※$p<0.05$ vs C.

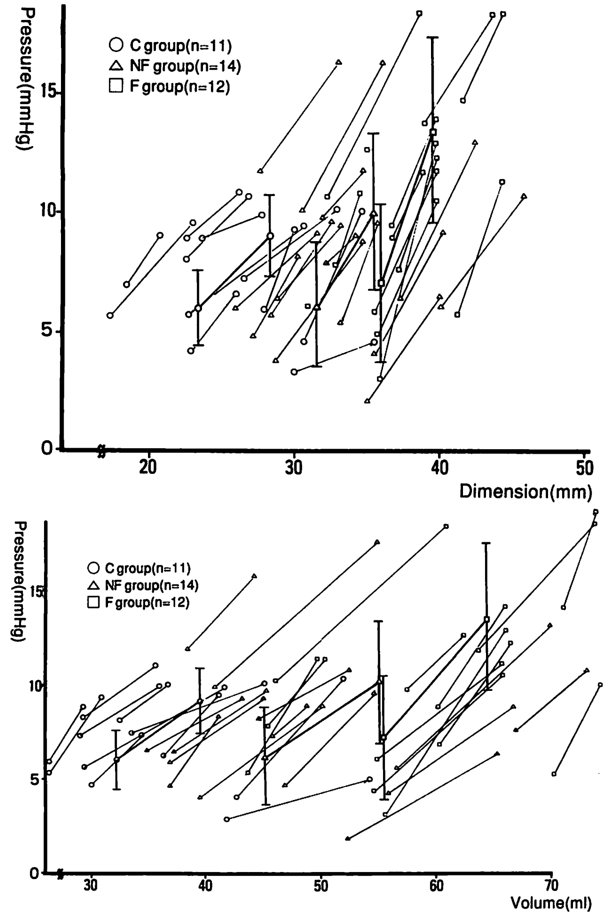

Fig. 4 Pressure-dimension plot (*upper*) and pressure-volume plot (*lower*) at mitral valve opening and pre-atrial contraction

Upper: In the F group, the plot was shifted toward the right and upward.
Lower: In the F group, this plot was also shifted toward the right and upward.

ours, but we used three points in the same patient (maximum, pre-atrial contraction, and minimum) and obtained a reasonably good correlation ($r=0.84$). We previously validated the accuracy of measurement of LA volume by biplane left atriography using ellipsoid phantom models[4]. Thus the accuracy of the calculated LA volume using the equation appeared to be acceptable.

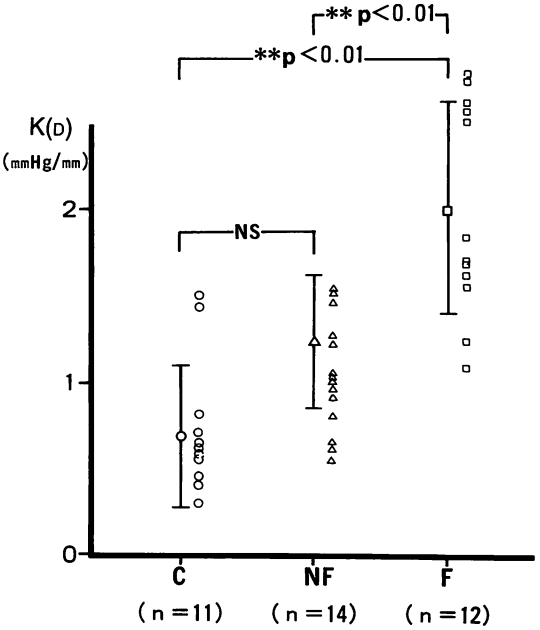

Fig. 5 Operative mean stiffness [K(D)] calculated from the left atrial dimension

The K(D) value was 0.69±0.40 mmHg/mm in the C group, 1.0±0.37 in the NF group, and 2.0±0.61 in the F group ($p<0.01$ in C vs F and NF vs F).
Abbreviations as in Fig. 4.

LA operative stiffness in myocardial infarction

LA booster function is increased in patients with myocardial infarction[7–9], and is ascribed to the preload increase of the LA (Frank-Starling's law)[10]. The LA booster function is observed in heart failure[23], but in extreme cases, an increase of contraction causes a decrease of this function because of afterload mismatch in various heart diseases[13,21,24]. LA contraction is thus important in the compensation of cardiac output.

Another important function of the LA is conduit function. This function aids in LV filling. In one experimental study[1], a more compliant LV resulted in more increased cardiac output. Another study[4] found that at the diastasis period of the LV, the LA is stiffer than the LV, and then blood fills in towards

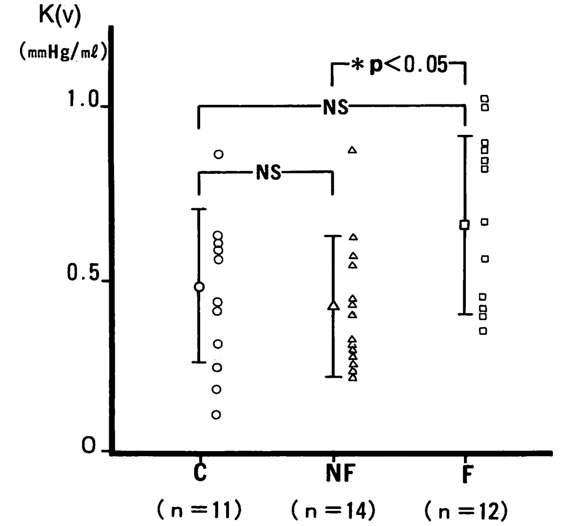

Fig. 6 Mean stiffness [K(V)] calculated from the left atrial volume

The K(V) value was 0.48 ± 0.23 mmHg/mm in the C group, 0.42 ± 0.19 mmHg/mm in the NF group, and 0.66 ± 0.25 mmHg/m*l* in the F group ($p < 0.05$ in NF vs F).

the LV. The LV peak filling rate is influenced greatly by LA pressure[3]. Thus, LA stiffness has an important role in LV filling. As the LA compensates for LV diastolic dysfunction, LA operative stiffness increases. The LA reservoir fraction was found to increase with age in a study of normal patients[25], indicating that LV dysfunction accompanying age is compensated for by LA reservoir function. The LA stores more blood, LA pressure increases accordingly, and as a result, LA operative stiffness increases. The same mechanism has been noted to occur in patients with myocardial infarction.

Clinical implications

In patients with myocardial infarction, LA contraction is important in maintaining cardiac output[7-9]. Our results suggest that the appropriate LA operative stiffness is also important. The measurement of LA operative mean stiffness can be easily performed by our new method using simultaneous recordings of LV pressure and M-mode echocardiography of the LA and mitral valve. We can obtain additional information about LV function by measuring the LA operative mean stiffness without left ventriculography, when left ventriculography is not advisable for the patients, *e.g.*, because of renal failure.

The trends observed in the LA operative mean stiffness were almost the same when calculated by the LA dimension and by the LA volume in the patient groups. Rather, LA operative mean stiffness calculated by the LA dimension was better than that by the LA volume in differentiating this values between the three groups. When K(V) normalized values [K(V)×LA volume] were used this index also increased significantly in the F group compared with other groups [K(V)×LA volume: 18.2 ± 8.9 (C), 22.5 ± 8.5 (NF), and 41.6 ± 12.9 mmHg (F), respectively; $p < 0.01$ in C vs F and NF vs F]. The LA operative mean stiffness calculated by the LA dimension was a better index than that by LA volume and can be easily used clinically.

Limitations

The operative stiffness obtained by our method was the mean stiffness from point B to point C (**Fig. 1**). The actual mean stiffness of LA is the slope of the line from A to C. In the clinical setting, the slopes of the two lines appeared to be almost the same because the pressure range was almost the same from A to C and from B to C. Empirically, point B lies close to the line of A to C, when the LA is supposed to be a tight chamber. However, it is actually not a tight chamber, and thus the slope of B to C was somewhat different from the slope of A to C. Although the differences were small, further study might be necessary. We did not compare the pressure derived from LV pressure using our method with the actual LA pressure; however, the usefulness of this method seemed to be supported clinically in our patient study.

We did not perform M-mode echocardiography of the LA and the mitral valve simultaneously. The LA dimension was obtained from simultaneous M-mode echocardiography of the LA and recording of the LV pressure. The LA dimension at the mitral valve opening was obtained as the maximum LA dimension (LAD_{max}). The LA dimension at pre-atrial contraction ($LAD_{pre\text{-}a}$) was obtained from the LA dimension at the time point just before the atrial contraction wave of the LV pressure recording.

The LV pressure at mitral valve opening (LVP_{mvo}) was obtained from the LV pressure at the time point of the mitral valve opening of the simultaneous M-mode echocardiogram of the mitral valve. The LV pressure at pre-atrial contraction ($LVP_{pre\text{-}a}$) was determined just before the atrial contraction wave of the LV pressure tracings.

Thus, all three recordings (M-mode echocardiogram of the LA, M-mode echocardiogram of the mitral valve, and LV pressure) were not recorded simultaneously. Some differences in the measurements may have been detected if they had been recorded simultaneously instead of separately, but we think that these differences would be negligible.

CONCLUSION

We measured the LA operative mean stiffness using simultaneous recordings of the LV pressure and M-mode echocardiography of the LA and mitral valve. Our results indicate that, in patients with depressed LV systolic function, the LA operative mean stiffness increased as compensation. Our method of measuring the LA operative mean stiffness can be obtained easily and can be used as a routine measurement providing additional information regarding LV function.

要　約

左室圧と左房および僧帽弁のMモード心エコー図との同時記録による平均作動左房スティフネスの評価

富田　政明　　加川　憲作　　野田　俊之
西垣　和彦　　藤原　久義

左房圧と左室圧は左房収縮時と僧帽弁開放時の2点で交差する．このことより，この2点での左房圧を左室圧から求めることができる．我々は左室圧と僧帽弁Mモード心エコー図の同時記録により僧帽弁開放時の左室圧(LVP_{mvo})，左室圧と左房Mモード心エコー図の同時記録の左室圧より左房収縮時の左室圧 ($LVP_{pre\text{-}a}$)，更にこの時点の左房径 ($LAD_{pre\text{-}a}$) と左房最大径(LAD_{max})を同時記録された左房Mモード心エコー図よりそれぞれ求め，これらより平均作動左房スティフネス [K(D), K(V)] の評価を行った．平均作動左房スティフネスの計測の前に，別に23例 (正常5例，狭心症4例，陳旧性心筋梗塞症14例) の患者における2方向の左房造影時の左房容積と，左房Mモード心エコー図による左房径最大容積時，左房収縮前，最小容積時の3点の比較から得られた回帰曲線を，以下の平均作動左房スティフネス [K(V)] の計測のために適用した．

対象は正常11例，陳旧性心筋梗塞で左室駆出率 (EF) 55% 以上の 14例，陳旧性心筋梗塞で左室駆出率55% 以下の12例，計37例である．左房径と左室圧より計測された平均作動左房スティフネス [K(D)] はこれら3群で 0.69±0.40, 1.0±0.37, 2.0±0.61 mmHg/mm で，EF 50% 以下の例では他より有意に大であった ($p<0.01$)．回帰曲線より算出された左房容積と左室圧より求めた平均作動左房スティフネス [K(V)] は 0.48±0.23, 0.42±0.19, 0.66±0.25 mmHg/m*l* で，やはりEF 50% 以下の例では他より有意に大であった ($p<0.05$)．このEF 50% 以下の例での平均作動左房スティフネスの増加は，僧帽弁開放時左房圧の上昇に起因していることが推測された．なお，左房径より求めても，左房容積に換算しても，平均作動左房スティフネスがほぼ同様の傾向を示したことより，簡易的に左房径より算出した平均作動左房スティフネスで代用しうることが示唆された．

このように我々の平均作動左房スティフネスを求める方法は容易であり，通常の心臓カテーテル時に施行すれば，左室機能に関する別の方向からの情報を得ることができると考えられた．

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