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Compensatory Changes in Atrial Volumes With Normal Aging: Is Atrial Enlargement Inevitable?

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OBJECTIVES The aim of this study was to evaluate left atrial volume and its changes with the phases (active and passive) of atrial filling, and to examine the effect of normal aging on these parameters and pulmonary vein (PV) flow patterns.

BACKGROUND Atrial volume change with normal aging has not been adequately described. Pulmonary vein flow patterns have not been volumetrically evaluated in normal aging. Combining atrial volumes and PV flow patterns obtained using transthoracic echocardiography could estimate shifts in left atrial mechanical function with normal aging.

METHODS A total of 92 healthy subjects, divided into two groups: Group Y (young <50 years) and Group O (old ≥ 50 years), were prospectively studied. Maximal (Vol_{max}) and minimal (Vol_{min}) left atrial volumes were measured using the biplane method of discs and by three-dimensional echocardiographic reconstruction using the cubic spline interpolation algorithm. The passive filling, conduit, and active emptying volumes were also estimated. Traditional measures of atrial function, mitral peak A-wave velocity, velocity time integral (VTI), atrial emptying fraction, and atrial ejection force were measured.

RESULTS As age increased, Vol_{max}, Vol_{min}, and total atrial contribution to left ventricle (LV) stroke volume were not significantly altered. However, the passive emptying volume was significantly higher (14.2 ± 6.4 ml vs. 11.6 ± 5.7 ml; $p = 0.03$) whereas the active emptying volume was lower (8.6 ± 3.7 ml vs. 10.2 ± 3.8 ml; $p = 0.04$) in Group Y versus Group O. Pulmonary vein flow demonstrated an increase in peak diastolic velocity (Group Y vs. Group O) with no corresponding change in diastolic VTI or systolic fraction.

CONCLUSIONS Normal aging does not increase maximum (end-systolic) atrial size. The atrium compensates for changes in LV diastolic properties by augmenting active atrial contraction. Pulmonary vein flow patterns, although diastolic dominant using peak velocity, demonstrated no volumetric change with aging. (J Am Coll Cardiol 2002;40:1630–5) © 2002 by the American College of Cardiology Foundation

The cardiovascular system is subject to the influence of normal aging (1) and is associated with altered myocardial structure (2) and impaired left ventricular (LV) relaxation (3,4). Atrial fibrillation (AF) is the most common arrhythmia, occurring in 0.4% of the general population, increasing to 5% in the population over 65 years of age (5). Of the patients with AF, 70% are older than 65 years, and in terms of multivariate predictors, age ranks second to heart failure as a risk factor for AF (6). Thus, normal aging may exert changes that increase atrial size and alter atrial function (7,8).

The atria act as a reservoir during ventricular systole, as a conduit (for blood from the pulmonary veins [PVs] to enter the LV) during early diastole, and as active contractile chambers that augment LV filling in late diastole. Overall the atria contribute up to 30% of cardiac output (9). Few studies have addressed the specific issue of atrial volume change or atrial contraction with normal aging. The aim of this echocardiographic study was to examine maximum left atrial (LA) volume (Vol_{max}) and its changes with active and passive LA emptying in a normal cohort. Together with pulmonary venous flow patterns, atrial volumetric changes can be employed to noninvasively estimate shifts in LA mechanical function with normal aging.

On the basis of these considerations, we hypothesized that: 1) maximal atrial volume would increase with aging; 2) active atrial emptying volume would increase with age-related decreases in LV diastolic relaxation; and 3) systolic PV flow would increase with aging.

METHODS

Study approval was obtained from the Committees for Human Research at Westmead and Liverpool Hospitals from Sydney, Australia. Sixty-three subjects were recruited from Westmead Hospital and 29 from Liverpool Hospital. In so far as possible, our subjects were representative of the normal population in that none had a history of ischemic heart disease, significant valvular disease, peripheral vascular or cerebrovascular disease, hypertension, or diabetes. None of the subjects were on cardioactive medications. The population considered was 103 volunteers, of which 11 (7 men and 4 women) were excluded. Six subjects had a remote history of hypertenison, four were on cardioactive medications, and one had poor echocardiographic images. A total of 92 individuals (30 men and 62 women), therefore, made

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Abbreviations and Acronyms

AF	= atrial fibrillation
BSA	= body surface area
CI	= confidence interval
LA	= left atrium/atrial
LV	= left ventricle/ventricular
PV	= pulmonary vein
2D	= two-dimensional
3D	= three-dimensional
Vol_{max}	= maximal left atrial volume
Vol_{min}	= minimum left atrial volume
Vol_p	= pre-atrial contraction volume
VTI	= velocity time integral

up the study cohort. Subjects were divided into two groups based on age: Group Y <50 years (range 17 to 49 years; mean age 32 years; n = 47) and Group O ≥50 years (range 50 to 86 years; mean age 63 years; n = 45).

Standard transthoracic echocardiogram. Doppler M-mode and two-dimensional (2D) echocardiography were performed according to established clinical laboratory practice using two commercially available instruments (System 1: Agilent/Philips Sonos 5500 (Andover, Massachusetts), System 2: General Electric/Vingmed System 5 (Horten, Norway) and offline measuring station Echopac) using harmonic 3.5 MHz variable frequency phased-array transducers. Left atrial antero-posterior size was estimated by M-mode measurement in the parasternal long-axis view (10). Left ventricular end-diastolic and end-systolic volumes were determined from the apical four- and two-chamber views using the biplane method of discs (11). Left ventricular stroke volume and ejection fraction were measured in all patients.

LA volumes and mechanical function. Left atrial volumes were measured at three points: 1) just before mitral valve opening (maximal LA volume or Vol_{max}); 2) at the onset of the P-wave on electrocardiography (pre-atrial contraction volume or Vol_p); and 3) at mitral valve closure (minimal LA volume or Vol_{min}). All volumes were calculated from apical four- and two-chamber zoomed views using the biplane method of discs (12,13). The following LA emptying function parameters were derived (8,14): LA passive emptying volume = $Vol_{max} - Vol_p$; LA passive emptying fraction = LA passive emptying volume/Vol_{max}; LA conduit volume = LV stroke volume − ($Vol_{max} - Vol_{min}$); LA active emptying volume = $Vol_p - Vol_{min}$; LA active emptying fraction = LA active emptying volume/Vol_p; LA total emptying volume = ($Vol_{max} - Vol_{min}$); LA total emptying fraction = LA total emptying volume/Vol_{max}. The total emptying volume and the active emptying volume of the LA were also estimated as a fraction of the LV stroke volume. Atrial volumes were indexed to body surface area (BSA) in all patients.

Mitral inflow and LV diastolic compliance. Mitral inflow velocity was obtained by pulsed-wave Doppler examination at a sweep speed of 100 mm/s from the apical four-chamber view by placing the sample volume at the tips of the mitral leaflets. Peak velocity of atrial contraction in diastole (A-wave velocity) was measured (15,16). The velocity time integral (VTI) of the A-wave was measured and the atrial fraction was estimated as A-wave VTI divided by the total VTI of mitral inflow (15,16).

Left ventricular diastolic performance was determined using standard echocardiographic parameters including peak E velocity, peak A velocity, E/A ratio, and deceleration time. These were obtained from the transmitral inflow pattern measured by pulsed-wave Doppler, with the sample volume placed between the leaflet tips. Doppler tissue imaging was used to acquire the E′ and A′ velocity, which measures the peak velocity of mitral annular ascent in early diastole and late diastole respectively. The E′ and A′ velocities were acquired by placing the sample volume at the septal annulus, recording at a sweep speed of 100 mm/s and measured as an average from 3 beats.

PV flow. Pulmonary vein flow velocities were recorded from the apical four-chamber view with the sample volume placed within the proximal 2 cm of the right upper PV. Color flow Doppler was helpful in aligning the Doppler cursor parallel to the pulmonary venous flow. Filter and gain settings were adjusted to minimize noise. Pulsed-wave Doppler signals were obtained at a sweep speed of 100 mm/s. Peak velocities and VTIs were measured for systolic and diastolic forward flow and for atrial reversed flow (17). The duration of atrial reversed flow was also measured. The systolic fraction of forward flow was estimated as systolic VTI divided by the total VTI of forward flow (17,18).

3D atrial volume. Vol_{max} and Vol_{min} were estimated using the biplane method of discs in all 92 subjects and from three-dimensional (3D) reconstruction of digitally acquired 2D images from apical four-chamber, two-chamber and long-axis views using a cubic spline interpolation algorithm (19), in a subgroup of 36 subjects who had been imaged using the System 2. Digitally stored images were measured offline using the System 2 offline measuring station.

Observer agreement. In 10 randomly selected studies from each group, two readers independently measured the 2D Vol_{max}, Vol_{min}, and Vol_p as well as PV flow parameters including peak velocities and VTIs of forward systolic and diastolic flow and reversed atrial flow. One observer remeasured the same 20 studies at a separate time to determine intraobserver agreement.

Analysis. All values are expressed as a mean ± SD. Differences among the groups were examined by a two-sample Student *t* test. Simple regression was used to examine the relationship between age and Vol_{max}, Vol_{min}, passive emptying, passive emptying fraction, conduit volume, active emptying volume, and active emptying fraction. Bland-Altman analysis (20) was performed to analyze intra- and interobserver variability. Data were analyzed using Statview Student (version 4.0, Abacus Concepts Inc., Berkley, California) and SPSS (version 10.0, Chicago, Illinois).

Table 1. Demographic and Echocardiographic Variables of the Two Groups (Mean ± SD)

	Group Y (n = 47)	Group O (n = 45)	p Value
Age (yrs)	32	63	
HR (beats/min)	71 ± 10	71 ± 12	NS
Systolic BP (mm Hg)	116 ± 10	124 ± 10	0.002
Diastolic BP (mm Hg)	74 ± 7	76 ± 7	NS
Body surface area (m^2)	1.85 ± 0.23	1.77 ± 0.24	NS
LA diameter (M-mode) (mm)	36 ± 4	36 ± 6	NS
E velocity (m/s)	0.85 ± 0.2	0.74 ± 0.2	0.006
A velocity (m/s)	0.59 ± 0.1	0.78 ± 0.2	0.0001
E/A <1	1.5 ± 0.4	0.97 ± 0.3	0.0001
DT (ms)	199 ± 29	200 ± 24	NS
A VTI (cm)	7.9 ± 3.1	11.2 ± 3.9	0.0001
Atrial fraction (%)	35.4 ± 8.7	46.5 ± 9.7	0.0001
E′ vel (cm/s)	10.3 ± 2.6	6.5 ± 1.6	0.0001
A′ vel (cm/s)	8.5 ± 1.4	9.8 ± 1.8	0.0005

A vel = peak mitral inflow atrial contraction velocity; A′ = peak atrial contraction velocity using Doppler tissue imaging; BP = blood pressure; DT = Deceleration time, E vel = peak velocity of early diastolic filling from transmitral flow; E′ vel = peak velocity of mitral annular ascent in early diastole using Doppler tissue imaging; HR = heart rate; LA = left atrium; VTI = velocity time integral.

RESULTS

A total of 92 patients divided into two groups (Group Y <50 years; Group O ≥50 years) were studied; the mean values for demographic, clinical, Doppler, and echocardiographic variables measured are listed in Table 1.

Atrial volumes. Left atrium dimension of maximal LA diameter using M-mode showed no significant difference between the groups. No significant difference was noted between the groups for absolute Vol_{max}, Vol_{min}, Vol_p, and total atrial emptying volume, as well as the volumes indexed to BSA. Passive emptying volume (14.2 ± 6.4 ml vs. 11.6 ± 5.7 ml: t = 2.1; p = 0.03) and conduit volume (35.2 ± 12.9 ml vs. 28.9 ± 10.4 ml: t = 2.6; p = 0.01) were significantly higher in Group Y versus Group O. When indexed to BSA, the passive emptying volume remained higher in Group Y but failed to reach significance. The active emptying volume and indexed volume were lower in Group Y when compared with Group O (8.6 ± 3.7 ml vs. 10.2 ± 3.8 ml: t = 2.0; p = 0.04). The passive emptying fraction was significantly higher (33 ± 7% vs. 27 ± 8%: t = 3.8; p = 0.0002), whereas the active emptying fraction was lower (30 ± 7% vs. 34 ± 7%: t = 2.5; p = 0.01) in Group Y compared with Group O (Table 2).

Subjects were further divided into upper and lower quartiles by age; Vol_{max} (40.6 ± 12 ml vs. 41.6 ± 11 ml; p = NS) and Vol_{min} (19.5 ± 6 ml vs. 20.1 ± 5 ml; p = NS) showed no significant difference between the two quartiles.

Atrial contraction versus LV stroke volume. Both total atrial emptying volume and active atrial emptying volume were estimated as a fraction of the LV stroke volume. The total atrial emptying volume was not significantly different between Group Y and Group O (40 ± 14% vs. 43 ± 14%; p = NS); however, the active emptying volume as a fraction of the LV stroke volume was significantly lower in Group Y (15 ± 5% vs. 21 ± 8%: t = 2.5; p = 0.01).

Table 2. LA Volumes and Fractions in the Two Groups

	Group Y (n = 47)	Group O (n = 45)	p Value
Vol_{max} (ml)	42.4 ± 15.5	40.9 ± 12	NS
Indexed Vol_{max} (ml/m^2)	23 ± 7.9	23.23 ± 6.1	NS
Vol_{min} (ml)	19.9 ± 7.9	19.2 ± 4.8	NS
Indexed Vol_{min} (ml/m^2)	10.6 ± 3.9	10.95 ± 2.8	NS
Vol_p (ml)	28 ± 10.2	29.4 ± 7.8	NS
Indexed Vol_p (ml/m^2)	15.26 ± 5.3	16.66 ± 4	NS
Passive Emp Vol (ml)	14.2 ± 6.4	11.5 ± 5.7	0.04
Indexed Passive Emp Vol (ml/m^2)	7.75 ± 3.3	6.56 ± 3	0.08
Conduit Vol (ml)	35.2 ± 12.9	28.9 ± 10.4	0.01
Indexed Conduit Vol (ml/m^2)	19.13 ± 6.6	16.4 ± 5.6	0.03
Active Emp Vol (ml)	8.6 ± 3.7	10.2 ± 3.8	0.04
Indexed Active Emp Vol (ml/m^2)	4.65 ± 1.9	5.71 ± 1.8	0.008
LA Total Emp Vol (ml)	22.8 ± 8.9	21.7 ± 8.2	NS
Indexed LA Total Emp Vol (ml/m^2)	12.4 ± 4.7	12.27 ± 4.1	NS
LA Total Emp Frac (%)	54 ± 7	52 ± 8	NS
Passive Emp Frac (%)	33 ± 7	27 ± 8	0.0002
Active Emp Frac (%)	30 ± 7	34 ± 7	0.01
LA Total Emp Vol/LVSV (%)	40 ± 14	43.7 ± 14	NS
LA Active Emp Vol/LVSV (%)	14.8 ± 5	20.6 ± 8	0.0001

Emp = emptying; Frac = fraction; LA = left atrium; LVSV = left ventricular stroke volume; Vol = volume; Vol_{max} = maximal left atrial volume; Vol_{min} = minimal left atrial volume; Vol_p = precontraction left atrial volume.

Atrial volumes and age. Age showed a modest correlation to the active emptying volume (r = 0.2; p = 0.05) and the active emptying fraction (r = 0.22; p = 0.03) by simple regression. An inverse correlation was noted when age was compared to the passive emptying volume (r = −0.23; p = 0.04), conduit volume (r = −0.23; p = 0.03), and the passive emptying fraction (r = −0.37; p = 0.0002).

PV flow. No significant differences were noted among groups for peak systolic velocity and VTI, diastolic VTI, atrial reversal peak velocity, and duration (Table 3). Peak diastolic velocity was noted to be higher in Group Y than in Group O (0.54 ± 0.1 m/s vs. 0.48 ± 0.1 m/s: t = 0.4; p = 0.01), whereas the ratio of peak systolic velocity and diastolic velocity was lower in Group Y (1.07 ± 0.3 vs. 1.24 ± 0.3; p = 0.006). No difference was noted in the systolic

Table 3. Pulmonary Vein Flow Parameters for the Two Groups (Mean ± SD)

	Group Y (n = 47)	Group O (n = 45)	p Value
Peak systolic velocity (m/s)	0.56 ± 0.1	0.57 ± 0.1	NS
Systolic VTI (cm)	14.3 ± 3.1	14.6 ± 4.3	NS
Peak diastolic velocity (m/s)	0.54 ± 0.1	0.48 ± 0.1	0.01
Diastolic VTI (cm)	11.3 ± 3.6	10.1 ± 3.2	NS
Peak AR velocity (m/s)	0.32 ± 0.1	0.31 ± 0.1	NS
AR VTI (cm)	4.4 ± 2.4	3.9 ± 1	NS
AR duration (ms)	180 ± 55	187 ± 51	NS
Peak systolic/peak diastolic ratio (%)	1.07 ± 0.3	1.24 ± 0.3	0.006
Systolic fraction (%)	56 ± 10	59 ± 8	NS

AR = atrial reversal; VTI = velocity time integral.

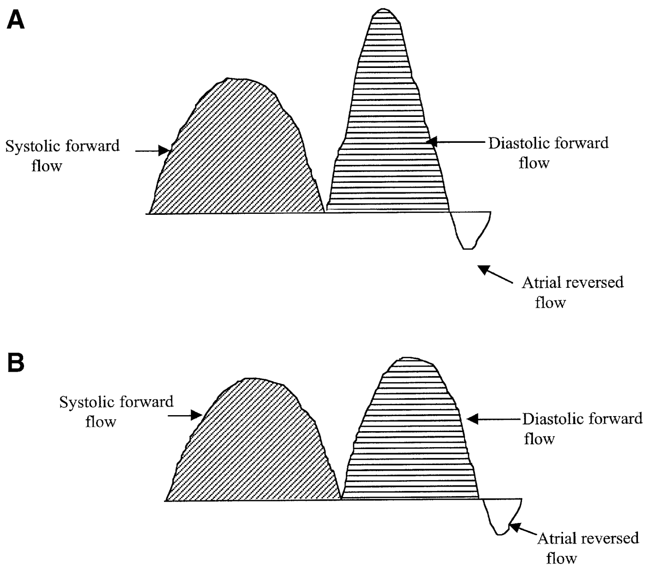

Figure 1. Diagrammatic representation of pulmonary vein flow pattern in young normal individuals **(A)** and old normal individuals **(B)**. Although the peak velocity of forward diastolic velocity in young individuals is higher than old individuals, the area under the curve remains unchanged. The **hashed lines** represent equal areas in both systole and diastole.

fraction between the two groups (56 ± 10% vs. 59 ± 8%; p = NS) (Fig. 1).

LV diastolic compliance. Left ventricular early diastolic relaxation was slowed with age, as demonstrated by transmitral flow pattern. In Group Y, E/A ratio was <1 in 2 of the 47 subjects. In contrast, in Group O, 26 of the 45 subjects (58%) had E to A reversal, indicating decreased diastolic compliance. The E′ velocity using Doppler tissue imaging was significantly higher in Group Y versus Group O (10.3 ± 2.6 cm/s vs. 6.5 ±1.6 cm/s: $t = 8.6$; $p = 0.0001$). Additionally, an inverse association was noted between age and E′ velocity ($r = -0.73$; $p = 0.0001$).

Three-dimensional atrial volumes. The Vol_{max} and Vol_{min} were estimated using the biplane method of discs in all subjects (n = 92) and in a subset of 36 subjects, by 3D reconstruction of digitally stored 2D images from the apical four-chamber, two-chamber, and long-axis views using software for the cubic spline interpolation algorithm available on System 2. In this subset of 36 subjects measured by both techniques, Vol_{max} by biplane was 37.2 ± 9.3 ml, and by 3D reconstruction, 37.7 ± 9.5 ml, whereas Vol_{min} was 17.5 ± 5 ml and 16.8 ± 5 ml respectively. The Vol_{max} and Vol_{min} estimated by 3D reconstruction correlated with biplane-derived volumes (Vol_{max} $r = 0.91$; $p = 0.0001$ and Vol_{min} $r = 0.88$; $p = 0.0001$). Bland-Altman analysis for 3D reconstruction versus biplane method showed a mean difference of −0.6 ml (95% confidence interval [CI] +3.4 to −3.6 ml) for Vol_{max} and a mean difference of 0.7 ml (95% CI +5.5 to −4.1 ml) for Vol_{min}.

Observer variability. Ten studies in each group were randomly selected for interobserver and intraobserver variability. The Vol_{max}, Vol_{min}, Vol_p, and PV flow parameters (peak velocities and VTIs of forward systolic and diastolic flow and reversed atrial flow) were remeasured by the same observer and by a second independent observer from the digital data using an offline system. Bland-Altman analysis was performed for Vol_{max}, Vol_{min}, and Vol_p and for the PV flow parameters. The mean difference and the 95% CI are reported in Table 4.

DISCUSSION

We have demonstrated that with normal aging, Vol_{max}, Vol_{min} and total atrial contribution to LV stroke volume are not significantly altered. However, the passive emptying and conduit volumes were noted to decrease with increasing age, with a compensatory increase in active atrial emptying volume. Decreased LV diastolic relaxation was noted with aging. Although the peak diastolic PV forward flow velocity was increased over the systolic peak in the younger group, PV flow when analyzed volumetrically (systolic and diastolic VTI) and systolic fraction of the total flow showed no significant difference between the groups.

The physiology of aging. Aging results in impaired LV relaxation. Previous studies have demonstrated age-related declines in indices representing LV diastolic properties (3,4). Transmitral Doppler inflow has demonstrated that velocity of early diastolic filling decreases with an increase in peak A velocity (E/A ratio) (21,22). Similarly, LV diastolic

Table 4. Bland-Altman Analysis for Interobserver and Intraobserver Variability

	Interobserver		Intraobserver	
Parameter	Mean Difference	95% CI	Mean Difference	95% CI
Vol_{max} (ml)	−0.2	2.4 to −2.8	−0.3	2.4 to −2.8
Vol_{min} (ml)	−0.24	1.6 to −2	−0.25	1.6 to −2
Vol_p (ml)	0.05	1.6 to −1.5	0.05	1.6 to −1.5
Peak PV systolic velocity (m/s)	0.003	0.08 to −0.07	−0.001	0.045 to −0.047
PV systolic VTI (cm)	0.1	1.7 to −1.5	0.11	1.2 to −0.9
Peak PV diastolic velocity (m/s)	0.001	0.06 to −0.06	−0.005	0.035 to −0.045
PV diastolic VTI (cm)	0.02	1.24 to −1.2	0.2	1.94 to −1.54
PV AR peak velocity (m/s)	−0.01	0.05 to −0.03	−0.04	0.38 to −0.3
PV AR VTI (cm)	−0.06	0.68 to −0.8	0.06	0.42 to −0.3

AR = atrial reversal; CI = confidence interval; PV = pulmonary vein; VTI = velocity time integral; Vol_{max} = maximal left atrial volume; Vol_{min} = minimal left atrial volume; Vol_p = precontraction left atrial volume.

function evaluated by Doppler tissue imaging has shown an age-related decrease in E′ velocity with an increase in A′ velocity (23,24).

Atrial size and aging. A few previous studies have reported that atrial size naturally increases with aging (7,8). Atrial fibrillation is well known to increase atrial size (25,26). These observations have often been linked, leading to the assumption that increased atrial size with aging may alter atrial function, increasing the likelihood of atrial arrhythmias (26–28). No volumetric study of atrial size has confirmed these observations. A previous study evaluating this question (7) compared young subjects with those of advanced age (>70 years) and found only subtle changes at the extremes of age. Similarly, in the study by Gardin et al. (8), differences were apparent only between the oldest and youngest groups (21 to 30 years vs. 70 years). Because the early studies demonstrating a major influence of age on LA size used the geometrically less rigorous M-mode method (29), we felt that it was appropriate to re-evaluate the correlation of aging to atrial size. In this study we quantitated atrial size using the volumetrically validated biplane method of discs (12) and in a subgroup estimated 3D atrial volumes. When we sought to measure the influence of age on atrial size, no significant difference was noticed between the two groups, or between the upper and lower age quartiles, suggesting that an increase in atrial size is an expression of pathology and is not part of normal aging.

Compensatory changes with aging. A decrease in LV relaxation with aging has been well demonstrated (3,4) and was also present in our cohort. Decreases in the passive emptying and conduit volume were noted with aging, similar to previous observations (7). Both these phases of atrial emptying occur during early diastole and are influenced by LV relaxation. However, as the total atrial emptying volume remains unchanged, the active emptying volume is increased in compensation for the decreased volume transfer. This increase in active atrial emptying volume is also reflected by the increase in peak A velocity, A-wave VTI, and atrial fraction in Group O.

PV flow pattern. Pulmonary vein flow into the LA is normally biphasic, composed of systolic and diastolic phases. Animal models have shown that during ventricular systole, PV flow is mediated by LA relaxation and by descent of the mitral annulus (30,31). During diastole, PV flow is affected by ventricular effects, with the atrium serving as a conduit. Previous studies have demonstrated that diastolic pulmonary flow is increased in younger individuals, with a progressive increase in systolic flow with aging (18). In this study we demonstrated that with aging, there is an increase in peak diastolic velocity with no significant increase in diastolic VTI. More interestingly, there was no significant increase in the systolic fraction with aging. These observations suggest that in youth, with brisk LV relaxation, a greater suction force is exerted on the atrium, causing more rapid emptying from the PVs. Thus, although the areas under the curves (volumes) remain similar, the peak diastolic velocity is increased. This observation indicates that diastolic dominant flow in young adults may need to be qualified as merely an increase in peak diastolic velocity because of brisk LV relaxation without representing a true increase in diastolic flow. Thus, VTI measurements need to be applied, to separate pathologic PV filling from those patterns normally seen in the younger individual (18,32).

Study limitations. There are several limitations of our study.

1. All subjects were recruited on the basis of a lack of history of cardiovascular disease, and normal LV size and systolic function and valvular function by echocardiography. It was not within the scope of the current study to perform exercise stress tests to evaluate the population more specifically for exercise capacity and exercise-induced wall motion abnormalities, particularly in the older group.
2. The reference standards used for comparison were previously used echocardiographic parameters. Performing invasive tests such as cardiac catheterization to evaluate LV diastolic pressure in normal subjects was not thought to be justifiable.
3. The cost of performing volume quantitation using magnetic resonance imaging, which is felt to be the noninvasive gold standard, was beyond the resources available for the study. However, previous studies have compared echocardiographic volumes with magnetic resonance imaging and noted an underestimation in LA volumes. This would be a systematic error that would not alter the comparisons among various volume parameters that are central to the findings of this study.
4. Subgroup analysis for each decade was not performed, as the sample size was thought to be too small for significant comparisons.

CONCLUSIONS

Our study suggests that, contrary to a widely held belief, normal aging does not increase maximum (end-systolic) atrial size. Rather than enlarge, the atrium compensates for the change in filling mandated by the inevitable occurrence of delayed LV relaxation by augmenting the volume of blood transported during atrial contraction while decreasing both passive and conduit volume. Pulmonary vein flow morphology changes with aging; however, volumetric analysis shows that alteration in peak velocity distribution is not reflected in volume change but is consequent to relaxation shifts. Atrial size does not increase as a consequence of normal aging from 20 to 70 years, and in this age group, atrial enlargement may result from associated atrial or ventricular pathology.

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