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Pulmonary venous flow reversal and its relationship to atrial mechanical function in normal subjects – Umeå General Population Heart Study☆

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Abstract **Aims** Although pulmonary venous flow reversal (Ar) is useful in the evaluation of left ventricular (LV) diastolic function, it is often difficult to study with transthoracic echocardiography (TTE). We determined the relationship between Ar and left atrial (LA) mechanical function and sought to define surrogate measurements for Ar.

Methods and results A total of 130 healthy subjects, mean age 54.3 ± 18.3 years, 62 women, were studied and classified into three groups: [young (Y), 25–44 years; $n = 44$], [middle-age (M), 45–64 years; $n = 43$] and [elderly (E), ≥ 65 years; $n = 43$]. Pulmonary venous flow and LV inflow studies were performed by TTE and LV basal free-wall motion was studied by Doppler tissue imaging (DTI). All images were acquired with a superimposed electrocardiogram. RR interval was similar in all groups while LA dimension and PR interval were increased in Group E vs. Y ($P < 0.001$). LA contraction (A_m) on DTI, transmitral A-wave (A) and Ar were simultaneous and started 84 ms after onset of P wave and this interval increased with age ($P = 0.02$). Similarly, the time intervals from the same landmark to peak A_m, A, and Ar were prolonged with age (all, $P < 0.001$). Despite this prolongation, peak A_m coincided with peak Ar in every age group ($r = 0.97$, $P < 0.001$) and Ar acceleration and deceleration times were consistently equal.

☆ The study was performed at the Norrlands University Hospital, Umeå, Sweden.

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Conclusion The timing of A_m obtained by DTI can be used to accurately estimate corresponding measurements of Ar recorded by TTE in subjects without cardiac disease.

Introduction

Pulmonary venous flow reversal (Ar) assessment by Doppler echocardiography provides additive value to the evaluation of left ventricular (LV) diastolic function. Studies have shown that the difference between Ar and transmitral A-wave (*A*) durations is a useful measure of LV end-diastolic pressure,[1,2] and it is also age independent.[3,4] Likewise, increased Ar to *A* velocity ratio is a useful marker for detecting elevated pulmonary capillary wedge pressure.[5,6] Clearly these indices highlight the diagnostic significance of the changes in the physiological relationship between forward flow (A-wave) and reversed flow (Ar-wave) during left atrial (LA) systole. This bi-directional flow, which is synchronous with LA contraction,[7] is influenced by loading conditions,[8,9] absent in atrial fibrillation,[10] and disturbed in conditions that present with impaired LV relaxation[11] including the elderly as part of the normal ageing process.[12] In order to optimise the diagnostic utility of these indices, imaging techniques applied should have the ability to delineate both flow patterns accurately and if possible simultaneously.

Transthoracic echocardiography (TTE) a commonly used method is less reliable in quantifying Ar;[13,14] its success rate in obtaining quality pulmonary venous (PV) flow recordings varies in some reports from 30–60%.[13,15,16] Further, the method overestimates Ar duration[17] and, to some extent, is equipment and operator dependent.[18] Despite these limitations, PV flow values obtained by TTE are comparable to those obtained by transesophageal echocardiography (TEE).[15] No study, however, has comprehensively explored the timing of Ar in relation to LA contraction with a view to identifying potential adjunct measurements for Ar.

This study, therefore, adopted non-invasive methods based on Doppler echocardiography and Doppler tissue imaging (DTI) to define regional and global atrial electromechanical events and their temporal relationships to Ar in a large sample of healthy subjects from young to the elderly. The study further sought to determine whether age had any effect on the timing of these events. Finally, we tested the hypothesis that the timings of A_m could be used as a marker of Ar obtained by TTE, since Ar is dependent on LA contraction.

Methods

Study subjects

One hundred and thirty participants (mean age 54.3 $\pm$ 18.3 years, range 25–88 years, 62 women) were consecutively studied and arbitrarily classified into three groups: Y (young), M (middle-age) and E (elderly). Group Y (25–44 years) consisted of 44 subjects; Group M (45–64 years) and Group E ($\geq$ 65 years) each consisted of 43 subjects. All study subjects were part of the Umeå General Population Heart Study, which consists of a cohort of 300 healthy volunteers aged 20–90 years; equal gender distribution in every age-decade, and all recruited from the Umeå General Population Register. All 130 participants had: (i) a normal clinical cardiovascular history and were not on any cardioactive medication, (ii) normal findings on physical examination including a 12-lead electrocardiogram (ECG), and (iii) clear analysable PV flow profiles on Doppler echocardiography with clear P waves on superimposed ECG were mandatory inclusion criteria for this study. Each participant gave informed consent and the local Ethics Committee approved the study.

Echocardiography

Immediately after physical examination and recording of a 12-lead ECG at rest, a complete M-mode, two-dimensional and Doppler examination was performed in each subject while lying in a left lateral decubitus position. Commercially available ultrasound system (Acuson Sequoia, Mountain View, Calf., USA) equipped with multi-frequency (2–3.5 MHz) imaging transducer was used. All studies were performed according to the recommendations of the American Society of Echocardiography using conventional views and measurements.[19] To minimise cardiac movement resulting from respiration, all echocardiographic

data were obtained at end-expiration. M-mode and Doppler traces were all recorded with superimposed ECG lead II showing clear P waves and phonocardiogram (PCG) at sweep speeds of 50 and 100 mm/s. The data were recorded on Magneto Optical Disks (Maxell Corp., New Jersey, USA) and later analysed off-line using the same ultrasound machine.

The transmitral flow (TMF) pattern was recorded using pulsed-wave Doppler technique with the sample volume positioned at the tip of the mitral valve leaflets on the apical four-chamber view. The peak early (*E*), late (*A*) diastolic velocities, the ratio of *E* to *A* and E-wave deceleration time (EDT) were also determined off-line. PV flow was obtained from the same view with the sample volume placed in the right superior pulmonary vein proximal to the LA guided by colour flow Doppler.

Myocardial DTI was performed with the sample volume placed at the endocardial border of the base of the LV lateral wall from the apical four-chamber view. The wall motion velocity pattern was recorded and expressed as: systolic wave (S_m), early diastolic wave (E_m) and late diastolic wave (A_m) (mid-panel, Fig. 1).

Measurements and calculations

The following measurements were made from at least three different cardiac cycles.

Transmitral and pulmonary venous flow

(1) The time interval from the onset of P wave on the ECG to onset and then to the peak of:
   - A-wave of the TMF (P-A and P-pA, respectively) (Fig. 1);
   - Ar-wave on the PV flow (P-Ar and P-pAr, respectively).
(2) Duration, acceleration, deceleration times of A-wave and Ar. A-wave was measured from the onset to the cessation of the Doppler velocity profile.
(3) Peak A-wave and Ar velocities and their respective velocity—time integrals.
(4) PV systolic (*S*) and diastolic (*D*), velocities, time integrals and systolic fraction were derived.
(5) Isovolumic relaxation time (IVRT) as the time interval from A_2 (aortic component of the second heart sound) on the PCG to the onset of transmitral E-wave.

Doppler tissue imaging

(1) The time interval from the onset of P wave on the ECG to the onset and the peak of A_m (P-A_m and P-pA_m, respectively).
(2) Duration, acceleration, deceleration times, and peak velocity of A_m.
(3) Late diastolic temporal discordance (LDTD) was calculated as the difference between (P-pA) and (P-pA_m).
(4) Peak E_m velocity was measured and the E_m to A_m ratio calculated.

Two-dimensional apical 2 and 4 chamber

(1) LV end-diastolic and end-systolic volumes were determined using modified Simpson's formula and the LV ejection fraction (LVEF) was derived from these volumes.

LV end-diastolic and end-systolic, and LA dimensions were all measured from standard transverse M-mode echocardiograms. RR intervals and heart rate (HR) were measured from every image examined and a mean value obtained.

The onset of the P wave on the ECG was first derived by manually measuring the PR interval on the standard 12-lead ECG, using a digital calliper. To maintain the same PR interval in all the measurements performed on every subject, individual measurements were made in reference to R wave of the ECG, which is a more reproducible landmark. Hence, the distance from the peak of R wave to the onset of the preceding P wave (PR′ in Fig. 1, mid-panel) was determined and used throughout all measurements for each individual subject. This ensured a universal onset point of the P wave on every set of images studied thus eliminating possible errors associated with determination of the nadir point of the P waves.

Reproducibility of measurements

Intra-observer and inter-observer variabilities were tested in 22 subjects selected randomly from the three groups. Measurements, particularly timings and velocities upon which our conclusions are based, were repeated by one investigator and independently by a second at different times to determine intra- and inter-observer variability. Results were analysed using the method of agreement as described by Bland and Altman[20] and presented as the coefficient of variation.

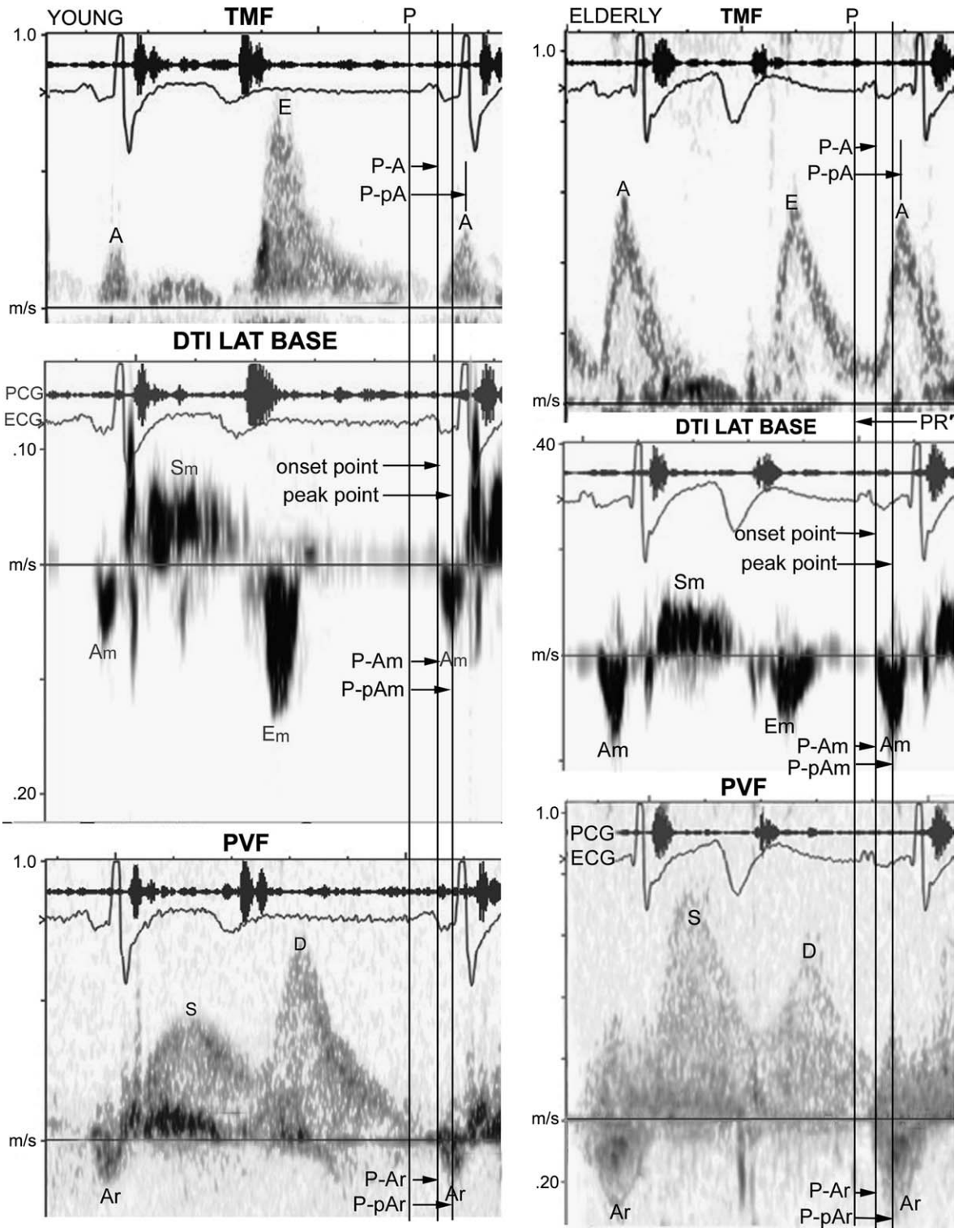

Figure 1 Vertical lines show specific landmarks for time measurements in the cardiac cycle. Late diastolic timing relationships between A_m, Ar and A-wave with respect to the onset of P wave on the ECG in a young and elderly subject, respectively. All begin immediately after atrial contraction (*onset point*). A_m peaks at the same time as pulmonary reversal flow (Ar) (*peak point*), while *A* peaks later (late diastolic temporal discordance). PR′, interval from peak R on the ECG to the onset of the preceding P wave; P-A/P-Ar/P-A_m, from the onset of P wave to the onset of A-wave/Ar/A_m; P-pA/P-pAr/P-pA_m, from the onset of P wave to the peak of A-wave/Ar/A_m; and PCG, PVF, TMF, DTI, S_m, E_m, as described in the text.

Statistical analysis

All values are expressed as mean ± standard deviation. Comparison between groups was carried out by one-way analysis of variance (ANOVA) and correlation between variables by simple linear regression analysis. Student *t* tests for paired data were used whenever appropriate. Data analysis and calculations were performed using SPSS package (11.0, Chicago, Illinois) and the *P*-value was considered to be statistically significant when it was less than 0.05.

Results

General and echocardiographic features

There were no significant differences in the 130 study participants with regard to diastolic blood pressure, HR and the RR interval. In addition, LV systolic function measured by ejection fraction was normal across all age groups. Gender balance was maintained with an almost equal ratio of men to women in the entire study group. Other important demographic, clinical, Doppler and echocardiographic data are presented in Table 1.

Left atrial contraction: forward vs. reversal flow, and the effect of age

In Tables 2 and 3 comparisons are made mainly between Group Y (age <45 years) and Group E (age >65 years) to reflect LA contraction, corresponding timings and the effect of age. During atrial contraction the duration of A_m, forward flow (A-wave) and pulmonary reversal flow (Ar-wave) were all prolonged in the elderly compared to the young (114 ± 14 vs. 92 ± 13 ms; $P < 0.001$, 156 ± 16 vs. 143 ± 18 ms; $P = 0.001$, and 118 ± 12 vs. 106 ± 16; $P < 0.001$, respectively). Similarly, deceleration time (DT) was significantly prolonged (elderly vs. young) with respect to A_m (57 ± 11 vs. 45 ± 9 ms; $P < 0.001$) but had a modest change in the transmitral A-wave (83 ± 16 vs. 73 ± 16 ms; $P = 0.003$) and none in the pulmonary Ar (57 ± 9 vs. 54 ± 8 ms; $P =$ NS). Ar DT, however, showed a tendency to increase with age but did not achieve any level of significance. Overall, Ar DT was equal to the corresponding

Table 1 Demographic and echocardiographic variables (mean ± SD)

	Group Y ($n = 44$)	Group M ($n = 43$)	Group E ($n = 43$)
General			
Age (years)	34.0 ± 4.8	53.5 ± 7.5	75.9 ± 6.0
Sex (male:female)	30:14	15:28	23:20
Systolic BP (mmHg)	117 ± 12	126 ± 13†	141 ± 13†
Diastolic BP (mmHg)	74 ± 8	76 ± 9	76 ± 8
HR (beats/min)	67 ± 12	66 ± 8	67 ± 11
RR interval (ms)	921 ± 163	930 ± 112	909 ± 155
PR interval (ms)	163 ± 17	173 ± 20*	174 ± 18*
Echocardiographic			
LA dimension (mm)	33.5 ± 3.3	36.0 ± 4.5*	37.8 ± 4.7‡
LV EDD (mm)	47.9 ± 4.6	48.6 ± 4.4	46.9 ± 4.2
LV ESD (mm)	28.1 ± 4.0	28.4 ± 3.9	26.5 ± 4.1*
LV EF (%)	65.3 ± 5.2	62.8 ± 4.7	63.9 ± 5.7
E velocity (cm/s)	71.2 ± 13.4	63.1 ± 16.3*	57.9 ± 15.2‡
A velocity (cm/s)	44.9 ± 12.5	52.4 ± 13.8*	75.1 ± 14.1‡
E/*A* ratio	1.70 ± 0.58	1.24 ± 0.32‡	0.78 ± 0.17‡
IVRT (ms)	55 ± 13	71 ± 11‡	84 ± 18‡
EDT (ms)	167 ± 36	191 ± 36	231 ± 49‡
E_m velocity (cm/s)	18.6 ± 4.1	15.8 ± 3.6†	10.8 ± 2.4‡
A_m velocity (cm/s)	11.0 ± 2.9	13.9 ± 3.1‡	15.6 ± 2.5‡
E_m/A_m ratio	1.79 ± 0.59	1.20 ± 0.40‡	0.70 ± 0.15‡

A, peak late diastolic flow velocity; A_m, peak atrial contraction using Doppler tissue imaging; BP, blood pressure; *E*, peak early diastolic flow velocity; EDT, mitral E-wave deceleration time; E_m, peak velocity of basal LV motion in early diastole using Doppler tissue imaging; IVRT, isovolumic relaxation time; HR, heart rate; LA, left atrial; LVEDD/ESD, left ventricular end-diastolic/end-systolic dimensions; LVEF, left ventricular ejection fraction.
*$P < 0.05$, †$P < 0.01$ and ‡$P < 0.001$ compared to Group Y.

Table 2 Transmitral A-wave (*A*), pulmonary venous flow reversal (Ar), and (A_m-wave) Doppler-derived parameters (mean ± SD)

	Group Y ($n = 44$)	Group M ($n = 43$)	Group E ($n = 43$)
Mitral inflow A-wave			
Duration (ms)	143 ± 18	149 ± 13	156 ± 16†
Peak velocity (cm/s)	44.9 ± 12.5	52.4 ± 13.8*	75.1 ± 14.3‡
AT (ms)	70 ± 10	70 ± 9	75 ± 9*
DT (ms)	73 ± 16	79 ± 11	83 ± 16*
VTI (cm)	4.5 ± 1.2	5.2 ± 1.5	7.6 ± 1.3‡
Pulmonary venous flow Ar			
Duration (ms)	106 ± 16	113 ± 10*	118 ± 12‡
Peak velocity (cm/s)	19.9 ± 4.7	24.0 ± 3.5‡	28.1 ± 4.4‡
AT (ms)	52 ± 10	55 ± 6	61 ± 11‡
DT (ms)	54 ± 8	58 ± 7	57 ± 9
VTI (cm)	1.6 ± 0.5	2.0 ± 0.3*	2.4 ± 0.6‡
Doppler tissue A_m-wave			
Duration (ms)	92 ± 13	102 ± 11*	114 ± 14‡
Peak velocity (cm/s)	11.0 ± 2.9	13.9 ± 3.1‡	15.6 ± 2.5‡
AT (ms)	46 ± 7	53 ± 6‡	57 ± 8‡
DT (ms)	45 ± 9	50 ± 9	57 ± 11‡

A-wave/Ar, mitral inflow/pulmonary venous flow reversal at atrial contraction; A_m, (as in Table 1); AT, acceleration time; DT, deceleration time; VTI, velocity–time integral.
*$P < 0.05$, †$P < 0.01$ and ‡$P < 0.001$, vs. Group Y.

acceleration time (AT) (56 ± 10 vs. 57 ± 8; P = NS). The difference between Ar and A-wave durations had no correlation with age ($r = -0.18$; P = NS).

With advancing age there was a consistent increase in the corresponding peak velocities related to atrial contraction, (elderly vs. young): A_m (15.6 ± 2.5 vs. 11.0 ± 2.9 cm/s; $P < 0.001$), A-wave (75.1 ± 14.3 vs. 44.9 ± 12.5 cm/s; $P < 0.001$) and Ar-wave (28.1 ± 4.4 vs. 19.9 ± 4.7 cm/s; $P < 0.001$). Ar to *A* velocity ratio was ≈0.47 in the young and the middle-aged but significantly declined to ≈0.39 in the elderly ($P = 0.005$). Ar to A_m velocity ratio, however, was not affected by age ($r = -0.04$; P = NS) and remained ≈1.8 across all the age groups.

Effect of age on atrial electromechanical timings

The onset of atrial forward and reversal blood flow was synchronous with mechanical wall motion and all started approximately 84 ms after the onset of the P wave (Table 3). This electromechanical time interval tended to prolong with age ($P = 0.02$). Similarly, the time intervals from the same landmark to the peaks of Ar, A-wave and A_m were consistently prolonged as age increased ($P < 0.001$) (Fig. 2). In spite of this characteristic prolongation, peak atrial velocity coincided with peak reversal flow in every age group with an excellent correlation ($r = 0.97$; $P < 0.001$, Fig. 3). Peak A-wave, however,

Table 3 Temporal interrelations between atrial contraction (A_m), forward flow (A-wave) and pulmonary venous flow reversal (Ar) (mean ± SD)

Time measurements (ms)	Group Y ($n = 44$)	Group M ($n = 43$)	Group E ($n = 43$)
P to onset Ar	78 ± 14	83 ± 12	84 ± 15
P to peak Ar	129 ± 14	137 ± 13*	145 ± 18‡
P to onset A-wave	79 ± 14	86 ± 12	83 ± 13
P to peak A-wave	150 ± 13	157 ± 15	161 ± 14*
P to onset A_m	83 ± 15	86 ± 10	89 ± 13
P to peak A_m	129 ± 15	139 ± 11*	147 ± 17‡
[(P-pA)–(P-pA_m)]	22 ± 10	19 ± 13	13 ± 10*

A-wave/Ar, (as in Table 2); A_m (as in Table 1); P, electrocardiographic P wave; (P-pA) and (P-A_m), time intervals from onset of P to peak A and peak A_m, respectively.
*$P < 0.05$ and ‡$P < 0.001$ vs. Group Y.

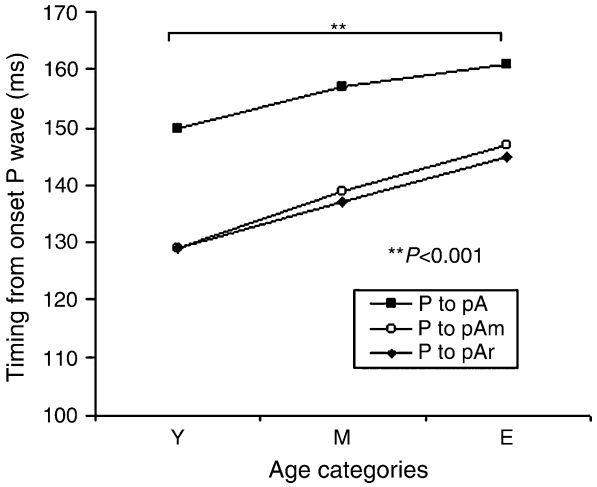

Figure 2 Age-related changes in the late diastolic time intervals — from onset P to the peaks of A, A_m, and Ar, respectively ($n = 130$). Mean values in different age groups young (Y), middle-age (M) and elderly (E) are shown.

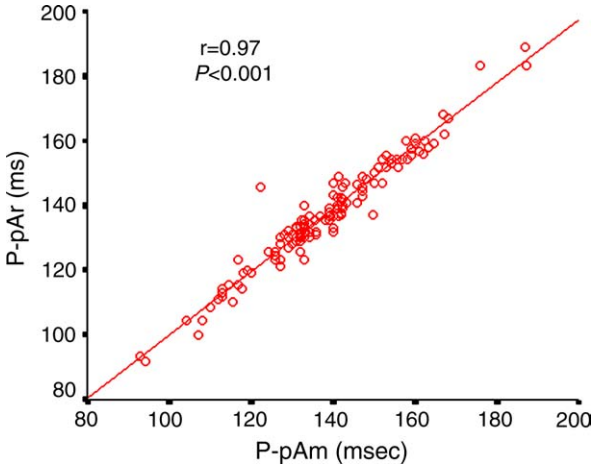

Figure 3 Scatter plot showing correlation between the time intervals to the peak of myocardial A_m (P-pA_m) and to the peak pulmonary flow reversal Ar (P-pAr), both measured from the onset of electrocardiographic P wave.

appeared approximately 20 ms after peak A_m in the young and the middle-aged, and this difference was significantly lower in the elderly ($P = 0.002$) (Table 3).

Effect of age on pulmonary velocities and atrial timings

Considering PV flow profile as a whole (Table 4), systolic flow velocity (*S*) increased ($r = 0.27$; $P = 0.002$) while diastolic flow velocity (*D*) decreased with age ($r = -0.51$; $P < 0.001$) and effectively *S* to *D* ratio increased ($r = 0.69$; $P < 0.001$). Furthermore, peak Ar velocity correlated with age ($r = 0.69$; $P < 0.001$). Similarly there was a good correlation between age and regional A_m duration and its corresponding velocity ($r = 0.66$; $P < 0.001$ and $r = 0.59$; $P < 0.001$, respectively). On the other hand, the timings to the peak of mechanical events measured from the onset of electrocardiographic P wave had only modest correlations with age P-A_m ($r = 0.46$; $P < 0.001$), P-pA ($r = 0.33$; $P < 0.001$) and P-pAr ($r = 0.46$; $P < 0.001$) (Table 4).

Reproducibility of measurements

There were no significant variations in the duplicate measurements. All measurements from DTI images and Doppler-derived peak velocities had the best intra- and inter-observer variability of 2—3%. However, the intra- and inter-observer variability for the duration of Ar and A-wave were within the range of 4—6%.

Discussion

This study comprehensively characterises and defines the timing of pulmonary venous flow reversal (Ar) in relation to other concurrent atrial mechanical events in a wide range of healthy subjects from young age to the elderly. The main findings of this study confirm that the onsets of Ar, transmitral A-wave (*A*) and atrial contraction (A_m) were all simultaneous. The most robust and consistent observation, however, was that peak Ar coincided with peak A_m across all age groups and the corresponding Ar to A_m velocity ratio was age independent. Peak Ar has previously been shown from M-mode and pulsed-wave Doppler studies to coincide with the peaks of interatrial septum[21] and longitudinal motion of the mitral annulus in late diastole[22] corresponding to LA contraction. However, with the advent of DTI accurate definition of time relationships between blood flow velocities and corresponding mechanical events in the cardiac cycle can now be easily obtained.[23—25] Thus, by using DTI to determine the time intervals in late diastole, this study defines a surrogate marker for the measurement of Ar obtained by transthoracic Doppler echocardiography (TTE).

Table 4 Correlations of Doppler variables and timings with age ($n = 130$)

Transmitral A-wave and pulmonary venous flow	*r* value	*P*-value
A-wave velocity	0.70	<0.001
A-wave velocity—time integral	0.72	<0.001
Pulmonary peak reversal flow velocity	0.69	<0.001
Pulmonary reversal flow velocity—time integral	0.62	<0.001
Pulmonary peak systolic velocity	0.27	0.002
Pulmonary peak diastolic velocity	−0.51	<0.001
Pulmonary systolic/diastolic ratio	0.69	<0.001
Pulmonary systolic fraction	0.57	<0.001
A_m-wave myocardial Doppler tissue imaging		
Duration	0.66	<0.001
Peak velocity	0.59	<0.001
Time intervals and timings		
electrocardiographic PQ interval	0.31	<0.001
P to onset A_m	0.20	0.02
P to peak A_m	0.46	<0.001
P to onset Ar	0.22	0.01
P to peak Ar	0.46	<0.001
P to onset A	0.20	0.02
P to peak A	0.33	<0.001
Ar duration	0.48	<0.001
A-wave duration	0.50	<0.001
Ar and A-wave duration difference	−0.18	NS

Abbreviations, as in Tables 1,2 and 3. NS, not significant.

Relationship between forward and retrograde blood flow during atrial systole

In healthy individuals LA contraction produces forward flow across the mitral valve (i.e. LV late diastolic A-wave velocity), as well as a small reverse flow in the pulmonary veins.[26] This bi-directional flow is synchronous with regional atriogenic lateral LV velocity in late diastole as clearly shown by this study. LV cavity pressure and compliance during atrial contraction affect forward and reverse atrial flow.[9] It is postulated that with decreased LV compliance, LA pressure will increase, during atrial contraction, and thus the reverse flow in the pulmonary veins will become relatively more prominent than the forward atrial flow across the mitral valve. Conversely, with increased ventricular compliance (which decreases LA pressure) as seen in the young, reverse flow in the pulmonary veins is decreased and forward flow is increased. The two mechanisms described generally reflect the physiologic atrioventricular changes that occur with advancing age, although it is expected that LV filling pressures remain normal or near normal in elderly persons with impaired diastolic filling.[27] Thus, decreased LV compliance observed in healthy elderly people is likely to influence the timings and extent of both forward and reversal flow during atrial contraction.

Timing of A-wave and Ar durations

Previous studies have attempted to measure the time duration of events that occur in late diastole by using the QRS complex of the ECG as the reference point.[14,21–23] In our study we sought to investigate these timings based on the hypothesis that late diastolic ventricular wall motion, transmitral forward flow (A-wave) and reversal flow into the pulmonary veins in normal subjects all depend on atrial contraction. We, therefore, used the onset of electrocardiographic P wave as the landmark to assess the time relationships between the onset of atrial depolarisation and these attendant mechanical events. Thus, we have demonstrated that both A-wave and Ar begin simultaneously after the onset of the P wave and are all synchronous with atrial contraction, and that this observation is consistent across all age groups. The tendency, however, for these time intervals to prolong with advancing age reflects the corresponding increase in the LA size and the PR interval.

Our results further show that peak atrial contraction strikingly coincides with peak reversal flow from the young to the elderly. This implies

that in normal hearts, irrespective of age, reversal flow into the pulmonary veins is solely dependent on atrial contraction, an observation consistent with previous studies that showed absent Ar in patients with atrial fibrillation.[10,21,28] The same pattern, however, is not observed in the forward flow (A-wave), which instead shows a diminishing time difference between the peak of A_m and that of A-wave with increasing age. Again, highlighting that the elderly population becomes increasingly dependent on atrial systolic function and late diastolic LV filling.

Duration and velocities of A-wave and Ar

Our study confirmed previous work[12,29,30] and partly contradicted others[3,4,14] by showing that Ar duration, time integral and extent of velocity increased with advancing age. In addition, we showed a characteristic pattern of sequential increase in Ar AT and DT, which to a lesser extent mirrored similar changes observed in the corresponding transmitral A-wave as age increased. However, Ar AT was similar to the DT and this pattern was maintained from the young to the elderly. We also confirmed that the difference between Ar and transmitral A-wave durations is age independent. Furthermore, our observation that the ratio of Ar to A_m velocity is also age independent merits further investigation as a potential sensitive marker for detecting decreased LV compliance.

Clinical application

Due to well known technical limitations,[18] determination of Ar by TTE remains difficult in some adult patients. In contrast, it is easy to obtain measurements from the corresponding long-axis motion of the cardiac base, particularly with DTI, even in sub-optimal images.[31] Therefore, in our study, by combining the two techniques, we have shown that the onset of Ar and A_m are simultaneous and the time to their respective peaks, determined from the onset of the P wave on the ECG, is coincident. Moreover, this study has demonstrated that AT and DT of Ar are equal. Accordingly, by determining the time to the onset and to the peak of A_m, Ar AT can be derived. Thus, the timing of A_m can effectively be used to estimate the duration of Ar particularly in normal subjects in whom Ar-wave profiles are not clearly defined. This remains, however, to be assessed in patients with different pathologies and severity of ventricular and atrial disease.

Limitations

Diastolic ventricular filling is influenced by a number of factors, particularly: HR, pre-load and afterload. To minimise these factors we studied healthy persons at rest and our results showed no significant variations in HR. With a significant number of persons aged above 70 years in the study, a possibility of incipient coronary artery disease (CAD) cannot be excluded without performing exercise testing and cardiac catheterisation. These procedures, however, were outside the scope of this study. We therefore relied on the absence of: symptoms, history of symptoms and family history of CAD to exclude the likelihood of CAD among the elderly. Although this does not guarantee the state of the coronary arteries, it appears to be a uniform limitation in all previous studies that have examined large numbers of healthy subjects.[12,14,17] A_m, Ar and *A* were technically not measured simultaneously, but rather from different cardiac cycles; however, HR was consistently similar in all recordings. Finally, this is a normal population study and therefore to achieve a wider generalisation of the results, our hypothesis will need to be tested in various disease conditions, especially specific situations where the duration of Ar has been used in clinical practice.

Conclusion

Peak atrial contraction coincides with the peak of atrial reversal flow into the pulmonary veins and this is consistent from the young to the elderly. Thus, the timing of regional atrial contraction by DTI can be used to accurately estimate corresponding measurements of pulmonary flow reversal obtained by transthoracic echocardiography in subjects with normal LA pressure.

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