The principal function of the left atrium is to modulate left ventricular (LV) filling and cardiovascular performance through reservoir, conduit, and booster pump functions; the latter is often (mistakenly) regarded synonymously with atrial function, and in contrast to the reservoir and conduit phases, has been studied extensively. Typically, the importance of atrial contraction has been estimated by measurements of cardiac output and end-diastolic volumes both with and without effective atrial systole, by relative LV filling using Doppler transmitral velocimetry (E/A ratios) or radionuclide angiography, or by atrial shortening using 2D echocardiography, angiography, and sonomicrometry. Despite considerable investigation, the magnitude and relative importance of the atrial contribution to LV filling and cardiac output remain controversial and provide motivation for a more complete evaluation of the atrial cycle. In this regard, nearly half of the LV stroke volume and its associated energy is stored in the left atrium during ventricular systole, which acts as a ventricular restoring force during the ensuing ventricular diastole. This reservoir function of the left atrium is governed by atrial compliance, which is most rigorously measured by mathematically fitting atrial pressure and volume data during ventricular systole. A number of studies have shown, however, that the proportion of left atrial inflow during ventricular systole with Doppler pulmonary venous flow (ie, S/D ratios) can estimate relative reservoir function. Thus, we showed that an isolated change in left atrial compliance alters predictably reservoir function and the pattern of pulmonary venous flow. Decreased atrial compliance is associated with greater phasic atrial pressures but a lower mean level of atrial pressure during ventricular filling, and as a result, a smaller end-diastolic volume and decreased venous return. In contrast, increased atrial compliance increases early LV filling and atrial systolic shortening.

Pressure-strain analysis in the intact dog has shown that for a given increase in atrial pressure, there is a greater increase in the end-diastolic atrial dimension and greater use of the Frank Starling mechanism in the appendage than body of the left atrium. The physiological and pathophysiological implications of the greater appendage than body distensibility are several-fold. First, the appendage may be particularly well suited to regulate intravascular volume, a role consistent with the high concentrations of ANP in that chamber. Second, increased systolic shortening in the appendage may function importantly in preventing stasis and thrombus formation in the stasis-prone appendage. Finally, greater distensibility of the appendage than body of the left atrium would be potentially beneficial in the context of increased ventricular filling pressures and decreased global distensibility.

Atrial fibrillation (AF) is the most frequent sustained arrhythmia in clinical practice, is associated with significant morbidity and mortality, and is challenging and often frustrating to treat. There is a tendency for AF to become chronic and more resistant to cardioversion with increasing duration of the arrhythmia, and although the details are poorly understood, persistence of AF is thought to result from the atrial remodeling that occurs. Although the obvious functional accompaniment of AF is the loss of atrial transport, atrial distensibility is reduced both acutely in AF and in response to the mechanical remodeling that occurs. It is not clear, however, whether mechanical remodeling is simply a marker for the electrophysiological changes that occur, in some way causally related, or is important only for final stabilization of the arrhythmia. Although the rhythm control strategy for AF has been dealt a blow by the results of the AFFIRM (Atrial Fibrillation Follow-up Investigation of Rhythm Management) trial, an important consideration in cardioversion of AF remains the ability to predict which patients successfully cardioverted from AF will remain in sinus rhythm.

The AFFIRM trial data notwithstanding, the potential benefits of restoring and maintaining sinus rhythm include symptom and rate control, improved hemodynamics, and reduced thromboembolic complications. Several clinical and echocardiographic predictors of recurrence in patients with successful cardioversion of AF have been proposed. Although maintenance of sinus rhythm is more likely in patients with shorter AF duration, smaller left atrial size, preserved LV and mitral valve functions, the predictive value of these parameters is poor. For example, data with respect to the impact of left atrial size on the successful maintenance of sinus rhythm are conflicting; whether this is attributable in part to alterations in atrial compliance merits further investigation.

Recent studies have suggested that left atrial appendage velocities measured before cardioversion predict long-term maintenance of sinus rhythm, although not all authors are in agreement. In a relatively large, multicenter prospective
study of successfully cardioverted AF patients, 91 (49%) remained in sinus rhythm and 95 (51%) had relapsed at the end of 1 year. Left atrial appendage peak anterograde flow velocity $>40$ cm/s was the strongest univariate predictor for maintaining sinus rhythm, followed by AF duration $<1$ week before cardioversion, left atrial diameter $<44$ mm, LV ejection fraction $>46\%$, absence of left atrial spontaneous echocardiographic contrast on TEE, and use of preventive antiarrhythmic drug during follow-up. Peak anterograde left atrial appendage velocity $>40$ cm/s (OR 5.2, 95% CI 2.7 to 10.1) and the use of preventive antiarrhythmic drug during follow-up (OR 2.0, 95% CI 1.0 to 3.8) were the only significant independent variables on multivariate logistic regression analysis. These data support the contention that left atrial appendage function is a critical determinant of the milieu requisite for atrial arrhythmia, although the reasons for this are uncertain. The regional differences in atrial appendage and body discussed above imply that the appendage is not acting simply as a surrogate for global atrial function.

Preliminary data in a dog model of pacing-induced heart failure suggest that left atrial functional alterations (as assessed by early to late diastolic transmitral and pulmonary vein A reversal velocity time integral ratios, left atrial kinetic energy, ejection force, and efficiency) caused by attenuation of mechanical remodeling have an impact on the ability to sustain atrial arrhythmia. An important limitation of these measurements is that they demand sinus rhythm, describe booster pump function only, require identification of atrial endocardial borders, and are highly sensitive to loading conditions. Measurement of myocardial strain and strain rate are newer indices that have the potential to overcome many of these limitations. Strain and strain rates represent the magnitude and rate, respectively, of myocardial deformation. Thus, during ventricular systole and late ventricular diastole, atrial strain and strain rates reflect atrial distensibility (irrespective of the underlying rhythm) and atrial contractility (in the presence of sinus rhythm), respectively.

In this context, the study by DiSalvo et al in this issue of Circulation is noteworthy. The authors predicted the 9-month AF recurrence rate in 68 patients after a successful cardioversion with tissue Doppler velocities and strain and indices from transthoracic and transesophageal echocardiography. Atrial strain and strain rates during ventricular systole, measures of atrial distensibility, and reservoir capacity were reduced in patients with AF compared with controls and predicted independently the maintenance of sinus rhythm. Although the tissue velocities themselves may be used to quantify atrial function, within a myocardial segment strain and strain rate, unlike tissue velocity, are less affected by translational movement and tethering. In addition, at least in the ventricle, strain and strain rate tend to be uniformly distributed across the myocardium (ie, without a base-apex gradient), which make strain and strain rate particularly well suited to the assessment of regional myocardial performance. Interestingly, none of the clinical or echocardiographic variables (except atrial appendage velocity) were different in the patients who maintained sinus rhythm and those in whom AF recurred. This disparity may have been caused by the relatively small sample size and nature of the low-risk (none AF) patient population, with normal LV systolic and mitral valve functions, mild LA enlargement, and short duration AF. Antiarrhythmic drugs were not employed, which may account for the unexpectedly high rate of AF recurrence. Therefore, it is important to generalize the results of this study cautiously to patients at higher risk. Nevertheless, DiSalvo and coworkers apply a novel, easily measured, theoretically sound index of atrial compliance, a neglected but critical component of atrial function.

A strength of the DiSalvo et al study is that atrial strain and strain rate during ventricular systole, reflecting atrial distensibility and reservoir capacity, respectively, were compared in multiple atrial regions in AF patients and controls; Doppler strain imaging of the appendage is a notable omission. Another strength is the correlation with Doppler measurements of pulmonary venous flow and early diastolic deceleration time (a measure of net atrioventricular compliance), which provide a measure of internal validity.

A few cautions regarding the use of tissue Doppler merit emphasis: First, tissue Doppler is exquisitely sensitive to the angle of insonation. Given that strain is three dimensional, with perpendicular vectors having opposite signs, angle deviation can have dramatic effects on strain rate calculations. For example, an angle change of $25^\circ$ can reduce peak longitudinal strain by 50%. Thus, the ability to align the ultrasonic beam parallel to the segment of interest is critical for accurate interpretation of strain rate. Second, present imaging technology allows instantaneous strain assessment only along the axis of ultrasound propagation; this is a potential problem in the atrium with its complex fiber orientation and relationship to the pulmonary veins. Third, spatial resolution varies with imaging and pulse length; adjustments to allow a sample distance between 5 and 10 mm generally allows for the best compromise between spatial resolution and background noise, but atrial myocardium is thin and tracking of the sample volume can be problematic. Fourth, strain and especially strain rate are noisy, and image and signal quality influence and may limit measurement of strain rate. Calculation of strain by integrating strain rates minimizes this error. Finally, strain rate does not directly examine contractility and is not load independent because stress (afterload) is not considered in its formulation. Despite these potential limitations, tissue Doppler estimates of left atrial pressure coupled with Doppler strain imaging during ventricular systole offer the promise of noninvasive atrial compliance calculation and when carefully validated will facilitate examination of the relationship between atrial remodeling, atrial reservoir function, and the inducibility and maintenance of AF.

**References**


KEY WORDS: Editorials atrium fibrillation cardioversion
Assessing Atrial Mechanical Remodeling and Its Consequences
Brian D. Hoit

Circulation. 2005;112:304-306
doi: 10.1161/CIRCULATIONAHA.105.547331
Circulation is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 2005 American Heart Association, Inc. All rights reserved.
Print ISSN: 0009-7322. Online ISSN: 1524-4539

The online version of this article, along with updated information and services, is located on the World Wide Web at:
http://circ.ahajournals.org/content/112/3/304

Permissions: Requests for permissions to reproduce figures, tables, or portions of articles originally published in Circulation can be obtained via RightsLink, a service of the Copyright Clearance Center, not the Editorial Office. Once the online version of the published article for which permission is being requested is located, click Request Permissions in the middle column of the Web page under Services. Further information about this process is available in the Permissions and Rights Question and Answer document.

Reprints: Information about reprints can be found online at:
http://www.lww.com/reprints

Subscriptions: Information about subscribing to Circulation is online at:
http://circ.ahajournals.org//subscriptions/