SUMMARY We have applied the new technique of dual echocardiography to determine the sequence of atrial contraction as reflected in the simultaneously recorded movements of the tricuspid and mitral valves. The study group included 29 normal subjects and 23 patients with either atrial flutter, coarse atrial fibrillation or atrial tachycardia with block. In normal individuals, right atrial contraction preceded left atrial contraction, with an average interatrial contraction time of 17 ± 8 msec. In contrast, the atrial contraction sequence was reversed in atrial flutter, with left preceding right atrial contraction and a prolonged interatrial contraction time of 82 ± 20 msec. In two patients with atrial tachycardia with block, atrial contraction was either simultaneous or left preceded right atrial contraction by a brief interval.

The sequence of atrial excitation, as determined by electrode catheter recordings from the right and left atria in one patient with atrial flutter and one patient with normal sinus rhythm, was the same as the contraction sequence. Left atrial pacing reversed both excitation and contraction sequences. After cardioversion of three patients from atrial flutter to normal sinus rhythm, interatrial contraction time was shortened but remained longer than in normal subjects, suggesting an interatrial conduction disturbance in patients with atrial flutter.

In coarse atrial fibrillation, the contraction sequence varied. Significant motion of both mitral and tricuspid valves coincident with fibrillatory waves occurred frequently, especially when the fibrillatory waves were coarse and regular.

Dual echocardiography permits the noninvasive determination of the sequence of atrial contraction and excitation, and may be useful in studying the characteristics of atrial arrhythmias.

DESPITE MANY STUDIES of the electrophysiological and mechanical characteristics of atrial arrhythmias, lack of satisfactory techniques has prevented simultaneous examination of the mechanical events in
Table 1. Underlying Cardiac Abnormalities in Patients with Atrial Arrhythmias

<table>
<thead>
<tr>
<th>Cardiac abnormality</th>
<th>Number of patients</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coronary heart disease</td>
<td>8</td>
</tr>
<tr>
<td>Cardiomyopathy</td>
<td>2</td>
</tr>
<tr>
<td>Non-rheumatic mitral regurgitation</td>
<td>2</td>
</tr>
<tr>
<td>of unknown etiology</td>
<td></td>
</tr>
<tr>
<td>Pericarditis</td>
<td>1</td>
</tr>
<tr>
<td>Hypertension</td>
<td>1</td>
</tr>
<tr>
<td>Chronic lung disease</td>
<td>3</td>
</tr>
<tr>
<td>Unknown</td>
<td>6</td>
</tr>
</tbody>
</table>

atrial intracardiac electrograms were recorded simultaneously with the dual echograms during spontaneous arrhythmias, after reversion to normal sinus rhythm and during right and left atrial pacing.

Materials and Methods

Patients

The study population consisted of 29 normal subjects, two patients with atrial tachycardia with block, 13 patients with coarse atrial fibrillation and eight patients with "common" atrial flutter. Electrocardiographic criteria for "common" atrial flutter followed Lewis' definition: continuous regular undulation of the baseline, with a prominent negative component of the F waves in lead II, III and aVF. In patients with atrial flutter, the atrial rate ranged between 250 and 438 (mean 300 ± 63). Table 1 presents the underlying cardiac abnormality in the patients with atrial arrhythmias.

Two patients, one with a regular atrial tachycardia with block and the other with multifocal atrial tachycardia with block, had digitalis intoxication, with atrial rates of 120 and 190/min.

Methods

Both the mitral and tricuspid valve echograms were recorded simultaneously utilizing a commercially available ultrasound device and two 2.25 MHz transducers with a diameter of 8 mm. One transducer was placed in the third or fourth left intercostal space and angled slightly upward or downward until the characteristic pattern of mitral valve motion was seen. The other transducer was placed in the same intercostal space or just below the first transducer and was angled upward and medially until the anterior leaflet of the tricuspid valve was seen. Multichannel photographic recordings were made at high paper speed (100 or 200 mm/sec) in order to visualize simultaneously the movements of the two valves as well as a phonocardiogram and ECG.*

Dual echocardiograms were recorded in all subjects during spontaneous normal or abnormal rhythm. Additionally, the sequence of atrial contraction was studied in three patients both before and after conversion of atrial flutter to normal sinus rhythm.

In two patients, electrode catheters were positioned fluoroscopically in the mid-portion of the coronary sinus and in the high lateral right atrium for recording left and right atrial electrograms, respectively. Dual echocardiograms were recorded simultaneously with the atrial electrograms in one patient during atrial flutter and in the other during sinus rhythm, as well as during right and left atrial pacing.

Analysis of Tracings

The morphologic aspects of tricuspid and mitral echograms were compared and the effects of atrial contraction on valve motion were related to the type of arrhythmia. Atrial dissociation (unilateral atrial flutter or fibrillation) was sought by analyzing the movements of the two atrioventricular valves.

The timing of atrial events was measured as an indication of the interatrial contraction and activation sequence.

The interval from the onset of the P wave in the ECG to the onset of the echocardiographic A wave (the opening movement produced by atrial systole) of the tricuspid (P-AOT) and mitral (P-AOM) valves was measured with vernier calipers. In patients with atrial flutter, we considered the nadir of the flutter wave in the ECG to represent the beginning of atrial activation, and measured from this point to the A wave in the tricuspid valve (F-AOT) and mitral (F-AOM) valve echograms. The interval from AOT to AOM was measured directly from the dual echocardiogram.

The precise time relations between atrial contraction and the A wave of the atrioventricular valves may be affected to an unknown extent by abnormalities of cardiac activation and performance. However, assuming a fairly close correlation between atrial contraction and the A wave, the sequence and timing of atrial contraction can be determined by examining the sequence of the tricuspid and mitral A waves. The interval from AOT to AOM approximates the difference in time of contraction of right and left atria, and will be referred to as the interatrial contraction time (IACT). The IACT provides a rough measure of interatrial conduction time, although this relation may also be affected by abnormalities of atrial and ventricular activation and performance. Interatrial conduction time estimated by dual echocardiography should not, of course, be expected to correspond closely with electrophysiologic measurements, even in normal subjects, because of differences in left and right atrial and ventricular hemodynamics. In addition, electrophysiologic measurements of interatrial conduction time may vary greatly, depending on the positioning of the recording electrodes.

Results

Normal Subjects

The 29 normal subjects had a uniform and reproducible sequence of atrial contraction as

*Irex — Continutrace Multichannel Recorder with dual echocardiographic capability.
**Figure 1.** Dual echocardiogram of the mitral and tricuspid valves in a normal subject. Right atrial contraction precedes left atrial contraction by 16 msec. TVE = tricuspid valve echogram, MVE = mitral valve echogram; AO<sub>T</sub> (dotted arrow) = onset of A wave in the tricuspid valve echogram; AO<sub>M</sub> (solid arrow) = onset of A wave in the mitral valve echogram. Recording speed is 100 mm/sec and time line is 40 msec.

**Figure 2.** Dual echocardiogram of the tricuspid and mitral valves in a patient with common atrial flutter. AO<sub>M</sub> occurred near the nadir of the flutter wave in lead II and preceded AO<sub>T</sub> by 80 msec.
Atrial Flutter

In contrast, in all eight patients with atrial flutter, left atrial contraction occurred near the nadir of the flutter wave in lead II and preceded right atrial contraction (fig. 2), with an average F-AOT interval of 0 ± 22 msec and an F-AOT interval of 82 ± 28 msec. Compared with normal subjects, IACT was greatly prolonged at 82 ± 20 msec (fig. 3). The IACT occupied 40 ± 10% of the atrial cycle.

Cardioversion from atrial flutter to normal sinus rhythm in three patients normalized the atrial contraction sequence and shortened IACT. However, IACT remained longer than normal at 40, 42 and 51 msec in these three patients after cardioversion (fig. 3).

Atrial Tachycardia with Block

One patient with multifocal atrial tachycardia with block showed either simultaneous contraction of both atria (fig. 4A and B) or left atrial contraction preceding right atrial contraction with an approximate IACT of only 40 msec (fig. 4C). In another patient with a regular atrial tachycardia with block, left atrial contraction preceded right atrial contraction, but an approximate IACT was only 30 msec. Thus, in these patients with atrial tachycardia due to digitalis intoxication, the sequence of atrial contraction differed from normal and IACT was less prolonged than in atrial flutter.

Atrial Fibrillation

Echocardiographic patterns of valve movement varied widely in the 13 patients with atrial fibrillation. Among these patients, four showed no important mitral or tricuspid valve motion in response to atrial activation. Eight others demonstrated motion of both mitral and tricuspid valves coincident with fibrillatory waves in the ECG (V1), especially when the fibrillary waves were coarse and relatively regular. In another patient, a number of rapidly changing patterns of valvular movements were observed. At times these...
changing patterns mirrored alterations in the morphology of the fibrillar waves in the ECG, with motion of both mitral and tricuspid valves coincident with coarse atrial fibrillation (fig. 5A), but there was no coordinated movement when fibrillation was fine (fig. 5C). This patient demonstrated movement of the tricuspid valve at times without any coordinated motion of the mitral valve (fig. 5B). These changing patterns of valve motion had no relation to the phases of respiration.

Combined Electrophysiologic-Echocardiographic Studies

Figure 6 shows the simultaneous recordings of a dual echogram of the mitral and tricuspid valves and bipolar right and left atrial electrograms in normal sinus rhythm. The sequence of atrial contraction as seen in the dual echogram is the same as the sequence of atrial excitation as recorded in the atrial electrograms; that is, right atrial excitation and contraction preceded left atrial excitation and contraction. The IACT (23 msec) determined from valvular events in the dual echogram, however, was shorter than the electrical interatrial conduction time (68 msec) obtained from the bipolar atrial electrograms.

Figure 7 illustrates observations utilizing the same technique of simultaneous dual echograms and bipolar atrial electrograms during high lateral right atrial pacing. Under these circumstances, right atrial excitation and contraction preceded left atrial excitation and contraction just as in sinus rhythm, as expected. The IACT obtained from the dual echogram (32 msec) was again shorter than the interatrial conduction time obtained from the bipolar electrograms (78 msec).

During left atrial pacing from the mid-coronary sinus, left atrial excitation and contraction preceded right atrial excitation and contraction, respectively. This sequence, the reverse of normal, is illustrated in

Figure 5. Dual echocardiogram of the mitral and tricuspid valves in a patient with coarse atrial fibrillation. (A) Significant motion of both mitral and tricuspid valves coincident with fibrillar waves. (B) Movement of the tricuspid valve coincident with fibrillar waves without any coordinated motion of the mitral valve. (C) No coordinated movement of either mitral or tricuspid valve. TVE = tricuspid valve echogram; MVE = mitral valve echogram; AO\textsubscript{M} (dotted arrow) = onset of A wave in the tricuspid valve echogram; AO\textsubscript{M} (solid arrow) = onset of A wave in the mitral valve echogram.

Figure 6. Simultaneous recording of dual echoes of the mitral and tricuspid valves and of bipolar atrial electrogram from the right and left atria through the coronary sinus in normal sinus rhythm. Both excitation and contraction in the right atrium precede their counterparts in the left atrium. TVE = tricuspid valve echogram; MVE = mitral valve echogram; AO\textsubscript{M} (dotted arrow) = onset of A wave in the tricuspid valve echogram; AO\textsubscript{M} (solid arrow) = onset of A wave in the mitral valve echogram; RA = bipolar electrogram from the right atrium; LA = bipolar electrogram from the left atrium.
FIGURE 7. Simultaneous recording of the dual echoes of the mitral and tricuspid valves and of bipolar atrial electrogram from the right and left atria (the latter through the coronary sinus) during the pacing of right atrium.

Right atrial excitation and right atrial contraction, respectively. Note every other pacing impulse (i.e. second and third impulse) fails to capture the atrium due to rapid pacing rate (250/min). TVE = tricuspid valve echogram; MVE = mitral valve echogram; AOTr (dotted arrow) = onset of A wave in the tricuspid valve echogram; AOAt (solid arrow) = onset of A wave in the mitral valve echogram; PI = pacing impulse.

Figure 8. Same technique as in figure 5, but with left-sided pacing. Left-sided excitation and contraction precede these phenomena on the right side. TVE = tricuspid valve echogram; MVE = mitral valve echogram; AOTr (dotted arrow) = onset of A wave in the tricuspid valve echogram; AOAt (solid arrow) = onset of A wave in the mitral valve echogram; RA = bipolar electrogram from the right atrium; LA = bipolar electrogram from the left atrium; PI = pacing impulse.

discussion
In previous papers from our laboratory, we have demonstrated the feasibility of analyzing the motion of two cardiac structures simultaneously by means of dual echocardiography. This technique permits simultaneous visualization of such combinations as mitral and tricuspid, mitral and aortic, or pulmonic and tricuspid valves. Using dual echocardiography to record mitral and tricuspid echograms, we have studied the sequence of atrial contraction in normal subjects and in patients with atrial flutter, atrial tachycardia with block and atrial fibrillation. Application of this technique to the present study requires the assumption that the onset of the A wave of the atroventricular valves closely coincides with the beginning of atrial contraction. The validity of this assumption is supported by the animal studies of Laniado and associates, who showed that initial echocardiographic mitral valve opening (D point) starts with the onset of transmitial flow, and of Pohost and associates, who demonstrated only slight delay between crossover of left atrial and ventricular pressures and the D point of the mitral echogram. Although these studies did not try to establish whether
mitral valve reopening corresponds equally well to flow and atrial pressure rise, it is reasonable to believe that an equally close relation probably exists. The assumption is further supported by the close correlation between the IACT of 20 msec, measured by Braunwald and associates, using right and left atrial pressure recordings, and the IACT of 17 ± 8 msec obtained by dual echocardiography in normal subjects in the present study.

Both the contraction sequence and the IACT differed in each of the rhythms studied. In atrial flutter, not only was the contraction sequence the reverse of normal, but the IACT was greatly prolonged. This prolongation may have been due in part to abnormal pathways of atrial excitation and interatrial conduction in atrial flutter. However, in the three patients with atrial flutter studied both before and after cardioversion, IACT remained more than twice as long as IACT in normal subjects. This prolongation of IACT after resumption of sinus rhythm implies an abnormality of interatrial conduction in atrial flutter, as also found by Leier and associates using invasive electrophysiologic recording techniques.

In atrial tachycardia with block, both atrial contraction sequence and IACT were variable, though the normal sequence of right before left atrial contraction did not occur in either patient. This variability probably resulted from differences in location of the origin of this arrhythmia. Because left atrial flutter is often preceded right atrial contraction, as in atrial flutter, atrial contraction sequence alone cannot differentiate between these two arrhythmias. However, IACT was shorter in atrial tachycardia with block than in atrial flutter. Although the number of patients studied was small, this observation suggests that measurement of IACT may help to distinguish between atrial tachycardia with block and atrial flutter, often a difficult distinction when the flutter rate is slow. This study did not include any patients with classical paroxysmal atrial tachycardia (PAT), now thought to result from reentry in the atrioventricular node. Therefore, our findings in atrial tachycardia with block due to digitalis intoxication cannot be applied to patients with classical PAT or with PAT utilizing accessory atrioventricular conduction pathways.

In atrial fibrillation, mitral and tricuspid valve A waves occurred only when the fibrillary waves were coarse, implying that large and relatively slow fibrillary waves correspond to enough coordination of atrial contraction to produce some hemodynamic effect. On the other hand, fine atrial fibrillation produced no important valvular movement, consistent with the ineffective atrial contraction thought to be usual in atrial fibrillation.

Atrial dissociation has been difficult to document in clinical practice, though it was demonstrated long ago in animals by Hering. As exemplified in one patient in this study with tricuspid but no important mitral valve motion during coarse atrial fibrillation, dual echocardiography may provide a noninvasive means for detecting atrial dissociation in man.

By recording simultaneous dual echograms and right and left atrial electrograms, we have demonstrated that the sequence of atrial excitation corresponds to the contraction sequence. That is, in normal sinus rhythm and with right atrial pacing, both right atrial contraction and excitation precede left atrial contraction and excitation. In contrast, in atrial flutter and left atrial (coronary sinus) pacing, both contraction and excitation sequences are reversed. However, the IACT determined echocardiographically does not equal the interatrial conduction time measured with electrode catheters in the high lateral right atrium and in the mid-portion of the coronary sinus. The disparity between echocardiographic and electrophysiologic measurements probably results largely from technical constraints on the placement of electrode catheters, which could not reliably be positioned close to the right and left atrial ends of the interatrial conduction pathways, even if those...
pathways were clearly defined.

Whether atrial flutter is due to reentrant or automatic mechanisms has been debated for decades. The findings of our study are compatible with either theory, and therefore contribute little to resolution of this controversy. On the one hand, our demonstration that left atrial contraction in atrial flutter occurs near the nadir of the flutter wave resembles the findings in other studies that appear to support the reentry, or circus movement, theory.12-14, 30 Additionally, these investigations12, 30 have demonstrated marked slowing of interatrial conduction in atrial flutter, which was thought to be a prerequisite for the development of reentry. However, the diffuse atrial disease that probably accounts for the slow conduction might also create conditions favorable to the appearance of a rapid automatic focus.

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