Two-dimensional Echocardiographic Phase Analysis

Its Potential for Noninvasive Localization of Accessory Pathways in Patients With Wolff-Parkinson-White Syndrome

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Background. In patients with the preexcitation syndrome who are undergoing transcatheter or surgical ablation, accurate localization of accessory pathways is critical. Because preexcitation is known to alter ventricular activation sequence and result in focal areas with presystolic contraction, we investigated whether phase analysis applied to two-dimensional echocardiographic cine loops objectively identifies these focal areas and can be used to localize ventricular insertion sites of accessory pathways.

Methods and Results. We prospectively obtained phase images in 17 patients (11 males; age range, 11–35 years) during minimal preexcitation in normal sinus rhythm and during maximal preexcitation induced by right atrial pacing. A group of 11 normal subjects (six men; age range, 26–37 years) served as controls. Pathway locations predicted from phase imaging were compared with those predicted from routine 12-lead ECGs, from visual inspection of cine loop images, and from catheter-mounted electrode endocardial mapping. Cross-sectional views in a digital cine loop format were mathematically transformed using a first harmonic Fourier algorithm to obtain the corresponding phase images. Phase angle histograms were derived in eight wall segments. Mean and earliest phase angles were derived by computer analysis to quantitate contraction sequence. We found that during right atrial pacing, phase angles in focal areas markedly deviated from normal—mean phase angles from 33° to 164°, and earliest phase angles from 50° to 180°. Accessory pathways could be precisely localized in 53% of the patients by 12-lead ECG, in 59% by visual inspection of cine loop images, in 82% by phase imaging, and in 94% by a combination of the three methods.

Conclusions. Our results suggest that phase imaging, especially when used in combination with cine loop and 12-lead ECG, can be used to localize ventricular insertion sites of accessory pathways and may be clinically useful as a noninvasive adjunct to endocardial mapping in patients with Wolff-Parkinson-White syndrome. (Circulation 1992;85:130–142)

In patients with Wolff-Parkinson-White (WPW) syndrome refractory to medical therapy, accurate localization of accessory pathways may help to identify candidates suitable for transcatheter or surgical ablation.¹ In current clinical practice, invasive electrophysiological testing (endocardial mapping) is used to localize accessory pathways, primarily by determining the earliest site of retrograde atrial activation during orthodromic supraventricular tachycardia.

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Several noninvasive techniques have been applied to localize accessory pathways. The 12-lead ECG,² supported in part by Grant-in-Aid 88 N120 from the American Heart Association, California Affiliate, Burlingame, Calif. E.H.B. supported in part by the Fannie Ripple Foundation, Annandale, N.J.

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body surface electrogram maps, and M-mode echocardiography have been shown to differentiate between anterior and posterior and between left- and right-sided accessory pathways. However, more precise localization of accessory pathways, particularly of septal pathways, which are most accessible to catheter ablation, has been limited.

Another method, first harmonic Fourier phase analysis of blood pool scintigrams, has been shown to objectively identify the sequence of ventricular contraction. The site of earliest “activation” so identified appears to usually predict pathway location and has also shown promise in the identification of septal pathways.

More recently, two-dimensional echocardiography has been shown to be useful in localizing accessory pathways by qualitatively determining earliest sites of myocardial thickening and endocardial inward motion from analysis of either digital continuous loop echocardiograms or two-dimensional guided M-mode tracings. Because phase analysis applied to two-dimensional echocardiograms objectively identified the abnormal ventricular contraction sequence in patients with right ventricular endocardial pacemakers, testing its role in localizing accessory pathways seemed worthwhile. Therefore, the purposes of the present study were to determine the ability of echocardiographic phase imaging to localize accessory pathways and to test potential advantages of this approach over visual inspection of digital continuous loop echocardiograms.

Methods

Experimental Approach

We prospectively applied echocardiographic phase imaging to normal subjects in normal sinus rhythm, to patients with WPW syndrome during minimal preexcitation associated with sinus rhythm, and during maximal preexcitation induced by right atrial pacing. Pathway locations predicted by echocardiographic phase imaging were compared with those determined by routine 12-lead ECG, by visual inspection of unprocessed two-dimensional echocardiographic cine loops, and by electrophysiological testing.

To estimate normal contraction sequence and abnormal contraction sequence in preexcitation, quantitative analysis of phase angle sequence was performed. An echocardiographic phantom mimicking ventricular contraction was designed to estimate random variation of regional phase angles.

We hypothesized that regional wall motion abnormalities seen in ischemia may also influence phase angle sequence and thus confound interpretation in patients who have both WPW syndrome and coronary artery disease. To test this hypothesis, we studied patients who had coronary artery disease and were undergoing coronary artery bypass graft surgery using intraoperative transesophageal echocardiography.

Study Population

We prospectively studied 11 normal subjects (six men; age range, 26–37 years; mean age, 31 years) and 20 consecutive patients with WPW syndrome who had single-accessory pathways localized by endocardial mapping. To avoid confounding variables, two patients with WPW syndrome and Ebstein’s anomaly and one patient with WPW syndrome and coronary artery disease were excluded from analysis. Therefore, the final study population consisted of 17 patients (11 males; age range, 11–35 years; mean age, 24 years). All patients with WPW syndrome were in sinus rhythm in their unprovoked state and had normal left ventricular function. Exclusionary criteria also included bundle branch block, although none was encountered. To investigate the hypothesis that regional wall motion abnormalities seen in ischemia affect regional phase angles, we studied 14 consecutive patients with coronary artery disease undergoing coronary artery bypass graft surgery using intraoperative transesophageal echocardiography. Two patients were excluded because of inadequate image quality (endocardial dropout). Therefore, 12 patients with coronary artery disease (one woman and 11 men; age range, 34–72 years; mean age, 61 ± 12 years) were included. A group of nine neurology patients (four women and five men; age range, 19–78 years; mean age, 49 ± 25 years) undergoing ambulatory transesophageal echocardiography (five to rule out patent foramen ovale and four to rule out atrial thrombi) served as a control group.

Study Protocol

All patients gave their informed consent to participate in the study protocol, which was approved by our committee on human research. In patients with WPW syndrome, echocardiographic studies were obtained during both sinus rhythm and right atrial pacing at the minimum rate (120–150 minutes⁻¹) required for maximal preexcitation within 1 hour after the completion of the formal electrophysiological study. Echocardiograms were obtained by an observer blinded to ECG and electrophysiological findings. A second observer performed right atrial pacing and recorded the standard 12-lead ECG. In intraoperative patients, two-dimensional echocardiograms were obtained after induction of anesthesia.

Procedures

A standard 12-lead ECG was recorded to document the stability of cardiac rhythm and degree of preexcitation during the image acquisition period.

Standard electrophysiological studies were performed. In brief, four 6F quadripolar catheters were inserted into peripheral veins and positioned against the high right atrium, across the tricuspid valve, at the right ventricular apex, and into the coronary sinus. To localize accessory pathways, the sequence of retrograde atrial activation was determined, ex-
ploring the tricuspid and mitral annuli during orthodromic supraventricular tachycardia.

Transthoracic two-dimensional echocardiograms were obtained using standard equipment (models 500 and 1000, Hewlett Packard, Andover, Mass.). To investigate endocardial inward motion and myocardial thickening close to the atrioventricular valve level, we obtained short-axis views at the base of the mitral leaflets and standard apical four-chamber views. Images were acquired at display depths of 16 or 20 cm with a sector angle of 60° or 90°, yielding a frame rate of 30–60 Hz, and then recorded on video tape.

Transeosophageal echocardiographic studies were performed using one of two commercially available monoplane transesophageal echocardiographic probes (Hewlett Packard; Aloka, Corometrics Inc., Wallingford, Conn.). In normal subjects, transesophageal studies were performed after subjects fasted for at least 6 hours. Aerosolized 10% lidocaine was used to achieve suppression of the gag reflex. The esophageal probe was then inserted in the left lateral position. Standard short-axis views were obtained at the level of the papillary muscle tips.

Digital Processing

To allow automatic transformation into a digital cine loop format, a single-lead ECG was displayed on the video screen of the ultrasound imaging system. Cross-sectional views were digitized in a 16-frame cine loop format (Cine View Plus, Freeland Medical Division, Indianapolis, Ind.) gated at the R wave upstroke. Cine loops were stored on high-density disks (960 k bytes, 60 k bytes/frame).

Phase Analysis

Images in the digital cine loop format were stored on a computerized image processor (View 2000, Virtual Imaging Company, Sunnyvale, Calif.) and mathematically transformed using first harmonic Fourier analysis. This transformation fits the time–intensity curve of each individual pixel (256 x 240 image matrix) with a first harmonic curve, characterized by its amplitude and phase angle. Here, amplitude simply relates to pixel intensity, whereas phase angle relates to the onset of intensity change. Phase angles were automatically transformed into intensity parameters and displayed in shades of gray relating to the amplitude of the structure analyzed. The spectrum of gray levels was color encoded using a cyclic color scale as previously described.7

With the equipment used in the present study, acquiring a 16-frame digital cine loop from video tape, storing it on the computer, and obtaining its phase image required a processing time of 6–8 minutes.

Interpretation of Fourier Phase Images

The color phase image displays the relative timing of intensity change of image pixels in a composite format. Applied to endocardial surfaces and chamber walls, the phase angle sequence relates to the sequence of wall thickening and motion.

The phase image interpretation was based on the following considerations and conventions. The first harmonic Fourier analysis algorithm fits the time–intensity curve of pixels with maximal amplitude at the R wave (and minimal amplitude in the middle of the cardiac cycle) to a pure cosine curve resulting in a phase angle of 0° (shades of green), whereas it fits the time–intensity curve of pixels with minimal amplitude at the R wave (and maximal amplitude in the middle of the cardiac cycle) to an inverted cosine curve and thus results in phase angles of 180° (shades of purple) (Figure 1, left panel). By convention, we evaluated areas in relation to maximal endocardial inward motion. Because maximal endocardial inward motion occurs near the middle of the cardiac cycle, especially at higher heart rates (Figure 1, right panel), the curve fit of the time–intensity curve of pixels in these areas can be expected to yield an inverted cosine curve. Therefore, by our convention, we expected normal wall motion to yield a phase angle near 180°.

The computer program provides serial highlighting of the color spectrum to identify pixels with identical phase angles and thus allows assessment of the phase or contraction sequence in a dynamic format. Because contraction is assumed to follow excitation, the sequence of phase angles is interpreted to mirror activation sequence.

Prediction of Accessory Pathway Location

Accessory pathway locations were predicted using 12-lead ECG, visual inspection of digital cine loops, and visual inspection of phase images.

From a surface 12-lead ECG recorded during atrial pacing, the locations of accessory pathways were determined using the orientation of the initial (40 msec) forces (delta wave) as previously described.2

From two-dimensional echocardiographic cine loops of multiple cross-sectional views, ventricular insertion sites of accessory atrioventricular connections were determined by identifying the site of presystolic myocardial thickening and endocardial inward motion in eight defined cardiac wall segments (Figure 2); this was done by an observer blinded to electrophysiological data. The short-axis circumference was divided into anteroseptal and posteroseptal, left anterior, left lateral, left posterior, right posterior, right lateral, and right anterior segments. Four-chamber views were divided into left posterior, posteroseptal, and right lateral segments.

From phase images, two observers determined the sites of earliest ventricular phase angles indicating presystolic/paradoxical wall motion. These areas were interpreted as ventricular insertion sites of accessory pathways. To compensate for a “learning curve effect,” observers were trained to interpret the phase image before the study. Structures in the echocardiographic cine loop that represented endocardium and myocardium were visually inspected to better identify the corresponding regions in the phase image.
Prediction of the pathway site was defined as "correct" when it was identical with the site of earliest retrograde atrial activation, as "ambiguous" when it included the correct site, and as "incorrect" when it did not include the correct site. Accessory pathway locations assessed by echocardiographic phase imaging were compared with those obtained from 12-lead precordial ECG, visual inspection of the two-dimensional echocardiographic cine loop, and endocardial mapping.

We also investigated the value of an approach combining the noninvasive methods tested in the present study.

Analysis of Regional Wall Motion

In intraoperative patients, wall motion was analyzed in five segments of the left ventricular short axis (anteroseptal, posteroseptal, inferior, lateral, and anterior) by two independent observers visually inspecting digital cine loops. Wall motion was graded as akinetic, severely or mildly hypokinetic, dyskinetic, or normal.

Phase Angle Histogram and Parameters

To objectively quantitate regional phase angles and phase angle sequence, regions of interest were drawn in the various ventricular wall segments to obtain phase angle histograms.

To identify the onset of maximal endocardial inward motion, we obtained minimal and mean phase angles in each wall segment. To exclude presumed artifacts, a threshold was used to omit analysis of pixels with phase angles occurring less frequently than 5% of the histogram peak. The range of phase angles (histogram width) in a single segment was determined to estimate the homogeneity of segmental contraction.
The phase angle sequence between segments was calculated for each cross-sectional view to estimate contraction sequence within the ventricle. The segment with the earliest phase angle in reference to the R wave (phase angle, $0^\circ$) was defined as the segment that contracted first. The phase angle delay of each segment was calculated.

**Random Variability of Phase Angle Parameters**

To estimate the variation of regional phase angles underlying the application of phase analysis to two-dimensional echocardiography, a phantom model mimicking homogeneous ventricular contraction was designed. Six water-filled latex balloons (150–250 ml) were positioned in a water bath, and echocardiographic short-axis cross sections of each balloon were recorded on video tape. In each balloon phantom, serial short-axis views, in a sequential hierarchy of size, were digitized in a cine loop format to yield an analog model of myocardial and endocardial phasic motion. Phase histograms were obtained from five segments along the balloon wall circumference corresponding to the end-systolic position of the ventricular endocardium. From these histograms, we obtained the minimal (earliest), mean, and range of phase angles. To estimate random variation in segmental phase angles, we calculated the upper 95% confidence limits of the differences in phase angles found between adjacent segments.

**Statistical Analysis**

Locations of accessory pathways predicted by noninvasive methods were compared with those obtained from endocardial mapping using contingency tables. To test for significant differences between the methods, we used Cochran’s test.

Because the distribution of phase angles in ventricular regions of interest has been shown to be non-parametric, data derived from phase angle values are given in median and 25% and 75% percentile values.

Friedman’s statistic was used to test the null hypothesis that the segmental phase angles were derived from one population. We used Wilcoxon signed rank test with the Bonferroni adjustment for multiple comparisons to test for significant differences between the segments.

Interobserver and intraobserver variabilities were determined for visual inspection of digital cine loops and phase images. To determine variability of phase angle measurements, we calculated mean absolute differences between measurements performed by two independent observers (interobserver variability) and between measurements performed by one observer on two different occasions (intraobserver variability) in a group of 10 randomly selected wall segments from patients with preexcitation.

**Results**

**Phase Image in Normal Subjects**

By visually inspecting the phase images, we found homogeneous phase angles in areas relating to maximal myocardial thickening and endocardial inward motion in all normal subjects. These phase angles were characteristically encoded in shades of purple (Figure 3).

**Phase Image in Patients With Preexcitation**

In patients with WPW syndrome during normal sinus rhythm, we found phase angles similar to those seen in
normal patients. However, during maximal preexcitation, we found focal segments with phase angles characteristically encoded in shades of green (Figure 4).

**Prediction of Accessory Pathway Locations**

In patients with WPW syndrome, endocardial mapping with catheter-mounted electrodes identified single-accessory pathways in all patients (Table 1): three left posterior free wall, one left lateral free wall, two right anterior free wall, seven posteroseptal, three anteroseptal, and one intermediate septal pathway.

Precordial 12-lead ECG was correct in nine patients (53%), ambiguous in six patients, and incorrect by guest on April 14, 2017 http://circ.ahajournals.org/ Downloaded from

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<td>Left lateral/anterior</td>
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Incorrect prediction of pathway location is shown in italics. Note that in patients with right anterior free wall pathways, both cine loop and phase image predicted adjacent locations.
Table 2. Noninvasive Localization of Accessory Atrioventricular Connections Using Different Approaches

<table>
<thead>
<tr>
<th>Approach</th>
<th>Segmentally Correct</th>
<th>Segmentally Incorrect</th>
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<tr>
<td>Phase echo/ECG</td>
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<td>Phase echo/cine loop</td>
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<td>ECG/phase image/ cine loop</td>
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</tbody>
</table>

*p<0.01 vs. ECG, cine loop. †p<0.05 vs. ECG, cine loop.

in two patients in predicting the precise pathway location (Table 2).

Visual inspection of digital continuous loop echocardiograms was correct in 10 patients (58%), ambiguous in four patients, and incorrect in three patients (Table 2).

Visual inspection of phase images was correct in 14 patients (82%), ambiguous in two patients, and incorrect in one patient.

In comparing individual methods, visual inspection of phase images was superior to visual inspection of cine loops or to ECG in correctly localizing accessory pathways (Table 2). Approaches localizing accessory pathways that combine information from the different analytic methods assessed in the present study showed significant variation. Although an approach combining information from both ECG and cine loop did not improve accuracy of either method alone, an approach combining echocardiographic phase imaging with ECG, cine loop, or both significantly improved detection of the precise pathway location.

Phase Angle Sequence in Normal Subjects

In the phantoms, the upper 95% confidence limit of phase angle differences between adjacent "wall segments" was 3.8° for mean phase angle and 6.8° for minimum phase angle. The histogram width in a single segment was 30° (range, 22–45°). The delay of phase angles between "earliest" and "latest" contracting segments was 6.5° (range, 3–12°) for mean and 15° (range, 5–20°) for minimal phase angles.

In normal subjects, phase angles were earliest in anteroseptal, left and right anterior, and left lateral segments with progression to posteroseptal and right posterior segments (Table 3). The delay of mean phase angles between earliest and latest contracting segments was 38° (range, 18–48°), whereas that of the minimal phase angle was 55° (range, 32–83°). The phase histogram width in single segments was 55° (range, 45–80°).

Phase Angle Sequence in Patients With Preexcitation

In patients with WPW syndrome during sinus rhythm, the delay of mean phase angles between earliest and latest contracting segments was 33° (range, 24–64°), comparable to that in normal subjects. However, with preexcitation during atrial pacing, this delay increased to 164° (range, 143–186°) (p<0.001) (Table 4). Similarly, the delay of minimal segmental phase angles increased significantly (p<0.001) from 50° (range, 23–121°) to 180° (range, 155–195°). In the focal segments analyzed as "preexcited" by visual inspection of phase images, the delay of mean phase angles increased from 13° (range, 3–36°) to 162° (range, 139–182°) (Figure 5).

Phase Angle Sequence in Patients With Regional Wall Motion Abnormalities

Wall motion abnormalities were found in all patients undergoing coronary artery bypass graft surgery (Table 5). In akinetic segments, there was a dropout in phase angles on the corresponding phase image. In areas with mild or severe hypokinesis, mean phase angles were delayed from normal (Figure 6). In patients with global hypokinesis, mean phase angles were not different from normal. In dyskinetic segments, phase angles were markedly delayed, comparable to those found in segments with preexcitation.

Interobserver and Intraobserver Variabilities

In predicting pathway location from phase images, agreement was present in 16 of 17 pathway locations (94%), both between and within observers. In predicting pathway location from cine loops, agreement was present in 15 of 17 locations (88%), both between and within observers. In measuring minimal and mean phase angles, interobserver variabilities were 20±24° and 15±9°, whereas intraobserver variabilities were 19±8° and 14±9°, respectively.

Discussion

Overall Findings

The results of the present study indicate that echocardiographic phase imaging can be used to objectively localize most accessory pathways, and it provides advantages over visual inspection of echocardiographic cine loops. Ventricular insertion sites of accessory pathways could be correctly identified in 82% of the patients using phase imaging alone and in 94% of the patients using an approach combining phase imaging with digital cine loop and ECG.

Relation Between Phase Angle and Wall Motion

The potential of echocardiographic phase imaging to localize ventricular insertion sites of accessory pathways may be explained by their effects on ventricular contraction. Both invasive studies using ventriculography19–21 and noninvasive studies using electrokymography22 demonstrated three phases of ventricular contraction in preexcitation. First, prematurely activated myocardium contracts, with spread
Wave yields phase angles markedly being closely related to the myocardium begins to contract. Third, the precontracting area is relaxing while the remaining muscle is contracting, resulting in paradoxical motion of the precontracting area. This paradoxical motion was identified on the phase image as focal areas showing phase angles markedly “delayed” from normal. This delay in phase angles may be explained by the method of gating cine loop images. Because precontracting areas have been shown to be activated approximately 100 msec after the beginning of the P wave for a duration of approximately 190 msec, \(^{21}\) the myocardial inward motion in preexcited areas can be expected to occur after the P wave on the ECG, thus being closely related to the QRS complex (Figure 7). Because cine loop images were gated at or near the R wave and our convention was to analyze maximal endocardial inward motion, normal contraction yields phase angles near 180°. Thus, it is logical that presystolic contraction with subsequent systolic relaxation yields phase angles near 0°, which are markedly delayed in reference to normal wall motion.

However, abnormal phase angle sequence is not a specific finding for preexcitation alone. We found that echocardiographic phase imaging is also sensitive to regional wall motion abnormalities in patients with coronary artery disease. Phase angles that were delayed from normal were found in mildly or severely hypokinetic and dyskinetic segments. This finding is in accordance with previous reports in the literature using radionuclide techniques, \(^{6,23}\) and may be best explained by delayed contraction (tardokinesis) often seen in ischemia. Therefore, when predicting pathway locations in patients with WPW syndrome who also have coronary artery disease, the presence of wall motion abnormalities is a confounding variable. Further studies are warranted to test the role of echocardiographic phase imaging in analyzing regional wall motion abnormalities. However, for that purpose, analysis of amplitude images should be included.\(^ {10,23}\)

### Potential Advantages of Echocardiographic Phase Imaging

Phase analysis may have advantages over M-mode echocardiography, 12-lead ECG, and visual inspection of cine loop echocardiograms.

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**Table 3. Absolute and Relative Regional Mean Phase Angles in Normal Subjects**

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</table>

Median as well as 25% and 75% percentile values are given for relative phase angles.

Mean phase angles are given for each wall segment (first row).

Corresponding relative phase angles indicate phase angle sequence between wall segments (second row).
TABLE 4. Relative Mean Phase Angles in Patients With Preexcitation

<table>
<thead>
<tr>
<th>Patient</th>
<th>Septal Anterior</th>
<th>Septal Posterior</th>
<th>Left Posterior</th>
<th>Right Anterior</th>
<th>Right Posterior</th>
<th>Apical four-chamber view</th>
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</table>

R, rest; P, right atrial pacing; shaded areas indicate pathway location assessed by endocardial mapping.

The pattern of inhomogeneous wall motion can be seen by M-mode echocardiography (Figure 8). However, M-mode echocardiography limits visualization of endocardial motion to a single beam, whereas phase imaging visualizes the temporal sequence of endocardial motion in a two-dimensional cross section. Preexcitation can also be seen by two-dimen-

sional echocardiography, especially when frame-by-frame analysis of computerized digital cine loop images is used. However, frame-by-frame analysis may be time consuming and subjective, whereas the

![Figure 5](http://circ.ahajournals.org/lookup/suppl/doi:10.1161/01.CIR.85.1.138/-/DC1/FIG5.pdf)

**FIGURE 5.** Plots of phase angle shift during preexcitation in patients with Wolff-Parkinson-White syndrome. Displayed is relative phase angle of endocardial motion related to pathway insertion site using earliest motion of normal endocardium as reference. This relative phase angle is expressed as “phase angle delay.” During sinus rhythm (unpaced), phase angle delay is low, indicating homogeneous normal contraction. However, during preexcitation (paced), phase angle delay increases markedly to 162°, indicating nearly paradoxical (phase angle shift, 180°) wall motion. This increase is explained by our conventions to use normal contraction as a reference and to gate cine loop at R wave and by the fact that preexcitation is a presystolic (late diastolic) event. Because phase images describe a periodic event in a cycle of 360°, phase angles appearing markedly “delayed” may in fact also be regarded as “early.” Horizontal lines indicate median values.
phase image of a single cross-sectional view can be obtained in and analyzed within 6–8 minutes and displays mechanical contraction in a more objective, simple format. With two-dimensional echocardiographic cine loops, motion is not conveniently displayed against time, and as a result, it may be more difficult to appreciate the site of premature contraction. This is supported by our finding that phase imaging was more accurate in predicting pathway location than were cine loop echocardiograms.

Another advantage of echocardiographic phase imaging may be that it allows quantitation of ventricular contraction sequence. The normal contraction sequence in various wall segments determined by echocardiographic phase analysis is in accordance with the activation sequence assessed by endocardial and epicardial mapping.

Our results suggest that echocardiographic phase imaging is superior to interpretation of precordial 12-lead ECGs in accurately localizing accessory pathways. Although delta wave polarity may be clinically useful in differentiating right- from left-sided and anterior from posterior pathway locations,2,27 it may be limited in its ability to differentiate septal from free wall locations, especially anteroseptal from anterior free wall. In the present study, precordial 12-lead ECG correctly identified six of seven posteroseptal pathways but was ambiguous in localizing anteroseptal pathways. In contrast, phase imaging correctly identified all septal pathways and allowed a clear differentiation between anterior and posterior locations.

Potential Limitations of Echocardiographic Phase Imaging

Several potential limitations of this study must be considered. The mathematical transformation of echocardiographic images using a first harmonic Fourier analysis algorithm may be limited because the curve fit to a cosine function may only be an approximation of the true time–pixel intensity curve.

By its influence on the relative duration of systole and diastole, heart rate may affect curve symmetry, which is known to influence the absolute regional phase angles,28 but the relative sequence of phase

\[ \text{FIGURE 6. Scatterplot of delay of contraction in patients with regional wall motion abnormalities (○) compared with normal subjects (●). Displayed is phase angle difference between earliest and latest contracting segments in each short-axis view. Horizontal lines indicate median values. Note that in two patients with global hypokinesis, phase angle delay was comparable to that of normal. In dyskinetic segments, phase angle delay was comparable to that found in preexcitation and consistent with paradoxical wall motion in systole.} \]

\[ \text{FIGURE 7. Abnormal timing of wall motion in preexcitation demonstrated by comparing M-mode echocardiogram of left ventricle in a normal subject (upper panel) with that in a patient with an anteroseptal pathway (2:1 preexcitation) (lower panel). In contrast to normal systolic septal motion (open arrow), preexcitation results in a septal contraction (closed arrow) that is closely related to P wave at time of mitral valve closure and results in paradoxical motion during systole. IVS, interventricular septum; LVPW, left ventricular posterior wall; ECG, electrocardiogram.} \]
angles between various regions of interest is unlikely to be affected by heart rate.

A variable quality of echocardiographic images is another factor limiting the applicability of echocardiographic phase imaging. Phase imaging applied to echocardiography depends on the presence of a clearly defined endocardial edge. In wall segments where clear visualization of the endocardium is not possible, meaningful phase angles, as a consequence, cannot be derived. This limitation may specifically apply for analysis of wall motion in right lateral ventricular segments. Therefore, integration of information obtained from multiple cross-sectional views appears to be especially important.

In addition, temporal resolution of echocardiographic images is limited by the sampling rate (30–60 Hz) of the ultrasound imaging system. Digitization of images into a cine loop format at 16 frames per cardiac cycle further decreases temporal resolution.

Another limitation of the phase technique may be that it depends on the degree of preexcitation. The sensitivity of two-dimensional echocardiography may not be sufficient to predict pathways in minimally preexcited patients. In minimally preexcited myocardium, the contraction amplitude may be smaller than the maximal ultimate contraction amplitude, and preexcitation may not be detected by phase imaging. This insensitivity is supported by the fact that phase imaging and cine loop technique detected the presence of preexcitation in only eight of 14 patients with sinus rhythm. In these eight patients, the QRS complex was wider than that in the six patients in whom the presence of preexcitation was not detected (138±18 versus 111±11 msec, p<0.001). However, during atrial pacing, the QRS complex was wide compared with that in sinus rhythm (141±14 versus 119±21 msec, p<0.01), and pathways could usually be predicted by phase imaging. The degree of preexcitation is crucial to the sensitivity of the phase technique. This is in accord with previously reported findings.29 Therefore, maximal preexcitation should be induced to provoke abnormal (paradoxical) motion in the preexcited areas (Figures 7 and 8).

Rotational and translational movements of the heart may also have influenced phase angle values30 but are unlikely to account for the phase shifts found in focal areas in patients with WPW syndrome during maximal preexcitation.

We must also consider that other conditions such as right ventricular volume or pressure overload, left bundle branch block,31 and right ventricular pacing17 have been shown to result in abnormal (paradoxical) septal motion. Other confounding conditions may include myocardial infarction and ischemia and constrictive pericarditis. Therefore, these potentially
confounding conditions must be excluded, especially when dealing with septal pathways.32

Furthermore, the earliest sites of retrograde atrial activation determined by endocardial mapping may not be precisely identical with the ventricular insertion site of accessory connections. This limitation would appear to result in relatively minor discrepancies33 well below the error of measurement using the phase image technique.

It must also be considered that right atrial pacing is suboptimal for inducing maximal preexcitation in patients with left free wall pathways, and coronary sinus pacing is a better approach. However, we found that maximal preexcitation could be achieved by modulating the paced rate.

Clinical Implications

Our results suggest that echocardiographic phase imaging, especially when used in combination with cine loop echocardiography and ECG, accurately predicts single-accessory pathway locations, is feasible, is readily available, and can be performed on a beat-by-beat basis. Fourier phase analysis is a simple computer method with the potential to be incorporated into standard echocardiographic imaging systems.

Echocardiographic phase imaging may be clinically useful as a screening method to localize accessory pathways as an adjunct to endocardial mapping. In performing a detailed electrophysiology study, a good idea of pathway localization beforehand is helpful to prepare for left heart catheterization (for left free wall pathways) or right coronary catheterization (for right free wall pathway) to precisely map the tricuspid annulus. The new era of catheter ablation for pathways in all locations makes it more important to have as much localizing data as possible available before the study.

However, to determine a clinically acceptable sensitivity of this approach, maximal preexcitation must be induced using either right atrial pacing or potentially transesophageal pacing.

In addition, further investigation is necessary to assess its potential role in patients with multiple accessory pathways and in patients with associated congenital heart disease and as a general method of identifying and quantitating wall motion abnormalities.

References

and characteristics of electrocardiograms. Circulation 1984;70:37–42

KEY WORDS: Wolff-Parkinson-White syndrome • Fourier phase analysis • echocardiography • imaging