JACC Vol. 18, No. 4
October 1991:1034–42

Detection of Changes in Atrial Endocardial Activation With Use of an Orthogonal Catheter

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The ability of a catheter with an orthogonal electrode configuration to sense differences in the direction of local atrial endocardial activation was tested in 18 consecutive patients with intact retrograde conduction. In all 18, discrimination of anterograde from retrograde conduction at a single atrial site was examined; in 5 of the 18, multiple sites were examined to determine if the discriminatory ability of the catheter was site dependent. The catheter was specially designed with bipoles in the x, y and z directions. A vector was computed for each electrogram during anterograde and retrograde conduction. Electrogram amplitude along the standard bipole was also compared for anterograde and retrograde conduction.

Mean electrogram amplitude for the standard bipole was significantly different for anterograde than for retrograde conduction in 17 of 18 patients (mean ± SD 4 ± 1.9 vs. 2.7 ± 1.3 mV; $p < 0.005$), with complete separation of amplitude distributions in 4 patients. The electrogram vector during anterograde conduction was significantly different from that during retrograde conduction in all 18 patients ($p < 0.0001$), with complete separation of vector distributions in 14. In some patients with multiple site recordings, the choice of site greatly affected separation based on electrogram amplitude or vector, or both.

The orthogonal catheter can be used to sense directional differences in local endocardial activation. The catheter shows promise for discriminating anterograde from retrograde conduction and examining the direction of endocardial activation in the heart during an electrophysiologic examination.

(J Am Coll Cardiol 1991;18:1034–42)

The primary purpose of this study was to test the ability of an orthogonal catheter to sense differences in the direction of local atrial endocardial activation. Orthogonal bipole configurations were first investigated by Goldreyer et al. (1,2) for use in atrial pacing leads. They found that leads with circumferentially located orthogonal bipoles offer better sensing characteristics than the more traditional unipolar and bipolar leads. Kadish et al. (3,4) used two orthogonal bipoles in a probe designed to measure the direction of local epicardial activation. After comparing the direction of activation with that during isochronal activation mapping, they concluded that vector loops generated by summing orthogonal bipole electrograms accurately represented the direction of local epicardial activation (3,4).

We hypothesized that an orthogonal bipole arrangement extended to three dimensions could be implemented in an intracardiac catheter to determine the direction of wave front propagation past the catheter. In this study, we initially tested the catheter in 18 patients by comparing the direction of activation during two distinct types of conduction.

Anterograde and retrograde conduction were chosen as examples of conduction leading to different atrial activation sequences on which to test the catheter. The discrimination of anterograde from retrograde conduction could also be useful in preventing some pacemaker-mediated tachycardias (5). To compare the discriminatory ability of the catheter with those of existing algorithms, we also measured and compared peak to peak amplitudes during anterograde and retrograde conduction.

Orthogonal electrograms were recorded in the high right atrium whenever possible. Although the right atrial appendage is a more common site to implant atrial pacemaker leads, mapping data suggest that such an isolated peninsula might not be a good location for detecting differences in atrial activation (6). The high right atrium is also readily accessible for both recording and implanting pacing leads. We thus chose the high right atrium as the initial site from which to record electrograms.

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Manuscript received November 5, 1990; revised manuscript received March 12, 1991, accepted April 1, 1991.

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0735-1097/91/$3.50

Table 1. Clinical Features of 18 Study Patients

Patient No.	Reason for EP Study	Underlying Heart Disease
1	SVT	Cardiomyopathy
2	Syncope	Mitral valve prolapse
3	Syncope	None
4	Near syncope	CAD
5	Syncope	AV node reentry
6	NSVT	CAD
7	Syncope	AV node reentry
8	NSVT	CAD,CABG
9	WCT	AV node reentry
10	Syncope	None
11	Syncope	AV node reentry
12	Syncope	None
13	SVT	None
14	SVT	None
15	NSVT	Possible myocarditis
16	Syncope	History of Afib, NSVT
17	Syncope	CAD,CABG
18	PSVT	WPW

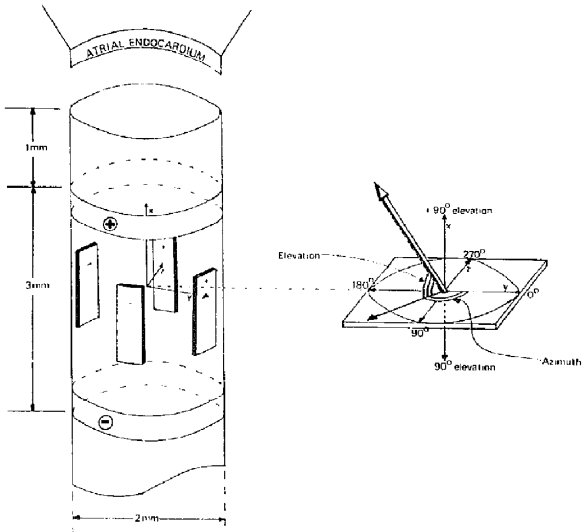
Afib = atrial fibrillation; AV = atrioventricular; CABG = coronary artery bypass graft; CAD = coronary artery disease; EP = electrophysiologic; NSVT = nonsustained ventricular tachycardia; PSVT = paroxysmal supraventricular tachycardia; SVT = sustained ventricular tachycardia; WCT = wide complex tachycardia; WPW = Wolff-Parkinson-White syndrome.

Methods

Study patients. Eighteen consecutive patients in sinus rhythm undergoing electrophysiologic testing who demonstrated intact retrograde conduction were included in the study. The patients' ages ranged from 30 to 73 years (mean 57). One patient had Wolff-Parkinson-White syndrome and four had atrioventricular (AV) node reentry. Indications for electrophysiologic testing and underlying clinical diagnosis for all 18 patients are shown in Table 1. The protocol of this study was approved on October 3, 1989 by the Evanston Hospital Institutional Review Board.

The orthogonal catheter. To compute the direction of atrial endocardial activation, an orthogonal 6F catheter (Webster, Inc.) was designed (Fig. 1). Two standard ring sensing electrodes were located, respectively, 1 and 4 mm

Figure 1. Schematic diagram of the orthogonal catheter and its orientation with respect to the atrium (**left**). The correspondence of elevation and azimuth to the catheter bipole orientation is also depicted (**right**). Because the rotation of the catheter and the angle the catheter makes with the atrial endocardium are fixed but unknown in a given study, anterograde and retrograde electrogram vectors can be compared with each other but not ascribed to any specific anatomic direction. In this diagram, a sample vector with an elevation of 60° and an azimuth of 120° is shown (**right**).



from the catheter tip. These two electrodes were used to record a "standard" bipolar electrogram and the x lead for orthogonal recordings. Four additional electrodes were located circumferentially around the catheter midway between the two ring electrodes with a bipole size of 2 mm. Opposite pairs of these circumferential electrodes were used to record the y and z leads for orthogonal recordings.

The catheter tip was slightly curved so that ideally the tip of the catheter would lie against the wall of the atrial endocardium with the "standard" bipole perpendicular to and the circumferential electrodes parallel to the endocardium. In practice, however, the catheter may not have maintained a perpendicular relation to the endocardium in each case. Also, because the rotation of the y-z axis relative to the atrium is unknown but fixed in a given study, the direction of activation can be compared for different activation sequences within the same patient but not in any direct relation to the anatomy of the heart or among different patients. Specific values for the electrogram vector must be interpreted with this in mind.

Data acquisition. For each patient, two introducer sheaths were inserted into the femoral vein with use of the Seldinger technique. The orthogonal catheter was advanced under fluoroscopy and placed against the endocardial wall of the high right atrium. Firm and stable contact with the endocardium was confirmed before each recording and reconfirmed at the end of each recording. A second standard pacing catheter was advanced to the right ventricular apex for ventricular pacing.

Sinus rhythm and retrograde conduction during ventricular overdrive pacing were recorded for 1 min each in each patient. The ventricles were paced rapidly enough to maintain 1:1 ventriculoatrial (VA) conduction with a constant VA interval. The orthogonal catheter position in the atrium was held fixed throughout both recordings. Surface leads I, II and V_1 and the three orthogonal intraatrial leads were filtered (0.05 to 5,000 Hz), amplified and recorded by an electrophysiologic recorder (Honeywell VR16; Electronics for Medicine) and stored on FM tape (Honeywell 101; Electronics for Medicine). Each recorded complex was examined individually and labeled as sinus rhythm or retrograde conduction. Premature atrial complexes, atrial electrograms recorded after premature ventricular complexes and possible atrial fusion complexes were excluded from the initial analysis and examined separately later.

Signal processing. The stored data were played back through a low pass antialiasing filter with a cutoff frequency of 200 Hz. Signals were given an appropriate gain and digitized at 1,200 samples/s on a Masscomp MCS-563 system (Concurrent Computer). Illustrations were produced on a Macintosh IICi computer (Apple Computer). A recursive digital high pass filter with a cutoff frequency of 30 Hz was employed to remove baseline wander and low frequency atrial repolarizations present in the signal.

Standard single bipole. With use of a previously described (7) peak detection algorithm, peak to peak amplitudes were measured from the "standard" bipole, which comprised two electrodes placed 1 and 4 mm, respectively, from the catheter tip.

Orthogonal electrograms. The electrogram vector during anterograde and retrograde conduction was then calculated for each electrogram in each patient. With vectorcardiographic techniques similar to those used with the Frank surface lead system (8), it is possible to calculate a three-dimensional vector loop for each electrogram. A vector sum over the appropriate region of the depolarization complex would then yield a single vector representing the overall direction of the vector loop.

To establish a consistent fiducial point in the center of the vector loop, a point was chosen at the half-area vector location of the loop (9). The area of the loop was first calculated by summing the area of the series of triangles that make up the loop. The point that best separated the loop area into two halves was then chosen as the fiducial point. The electrogram vector was then calculated by summing each of the three-dimensional vectors over a 17.5-ms window (21 data points) centered at this point. Because the high pass filter removes the direct current component of each of the signals, a vector sum over a long enough region of the signal will be 0. The 17-ms window was chosen because it is long enough to cover the prominent portion of the electrogram and short enough that the mean value is not "removed" by the high pass filter, which is 67.5 ms in duration. This procedure results in an electrogram vector that represents the direction of activation of each electrogram in each patient. The mean electrogram vector refers to the average direction of activation during the entire minute of anterograde or retrograde conduction.

The direction of the electrogram vector is described in terms of elevation and azimuth; the elevation is the angle the vector makes with the plane roughly parallel to the endocardium and the azimuth is the rotation of the vector's projection on that plane (Fig. 1). Thus, if the catheter were truly perpendicular to the endocardium, an elevation of +90° would reflect a vector pointing roughly from endocardium to epicardium, whereas an elevation of 0° would reflect a vector parallel to the endocardium. These two angles, elevation and azimuth, can describe the direction of any unique vector in three-dimensional space.

Because it is difficult to visually compare the vector distributions in three dimensions during a full minute of anterograde and retrograde conduction, a plot of elevation versus azimuth yields a more easily interpreted two-dimensional display.

Multiple site recordings. In 5 of the 18 patients, electrograms were recorded from multiple sites in the atria. In one patient, they were recorded from the left atrium through a patent foramen ovale. These multiple site recordings were used to investigate whether discrimination of anterograde from retrograde conduction on the basis of electrogram amplitude and vector was site dependent rather than to find the best site for discrimination. The location of the catheter was confirmed fluoroscopically. Electrogram amplitude and vector were computed at each site as previously described.

In one patient, two orthogonal catheters were placed at the mid and low lateral right atrium, respectively, allowing simultaneous recordings at two sites during anterograde and then during retrograde conduction. In the other patients, the multiple site recordings were made sequentially with a single orthogonal catheter.

Additional observations. As mentioned earlier, atrial electrograms recorded during premature atrial complexes and after premature ventricular complexes that were excluded from the initial analysis were later examined individually. For atrial electrograms recorded after premature ventricular complexes, only those that were early enough to confirm retrograde atrial capture were included. The electrogram amplitude and vectors of these electrograms were calculated as previously described.

Statistics. Student's unpaired *t* test was used to compare mean values for amplitude during anterograde and retrograde conduction in each patient. Because each mean vector is described by two variables (elevation and azimuth), Hotelling's T-squared statistic (10) was used to compare the direction of mean anterograde and retrograde electrogram vectors in each patient. Mean values were computed for each patient rather than pairing the mean values and computing an overall significance value because the spatial nature of the mean vector precludes it from being paired in any meaningful way. Amplitude data were analyzed similarly for consistency.

Two groups might have statistically different mean values, yet still be indistinguishable if their distributions overlap. We therefore used discriminant analysis (11) to determine how well anterograde and retrograde vector distributions could be separated into two groups. The elevation and azimuth of the electrogram vectors for each patient during anterograde and retrograde conduction were grouped together. The linear discriminant function that best separated the two groups was then calculated. The percent of points correctly assigned to their appropriate group was defined as "percent separation." This analysis was performed with use of the SPSS statistical package (12).

The percent separation was calculated similarly for amplitude measurements. Values are expressed as mean values ± SD.

Results

The initial analysis compared electrograms recorded during anterograde and retrograde conduction from a single site in each of the 18 patients. An average of 70 electrograms (range 42 to 96) recorded during anterograde conduction and 100 electrograms (range 71 to 149) recorded during retrograde conduction were available for analysis in each patient.

Standard single bipole (Table 2). We initially examined the ability of the standard single bipole to discriminate anterograde from retrograde conduction on the basis of electrogram amplitude alone. The mean amplitude of the electrogram during anterograde conduction was significantly different from that during retrograde conduction in 17 of 18 patients (4 ± 1.9 vs. 2.7 ± 1.3 mV, $p < 0.005$). In Patient 17, there was no significant difference. Complete (100%) separation between anterograde and retrograde amplitude ranges was observed in only 4 of the 18 patients, although >85% separation occurred in 13; in the remaining 5 patients, separation ranged from 55% to 74%.

Table 2. Summary of Atrial Electrogram Data Recorded at a Single Site in 18 Patients

	Amplitude			Vector	
Patient No.	Ante* (mV)	Retro* (mV)	Sep (%)	Theta (degrees)	Sep (%)
1	4.48	2.25	99	97	100
2	7.36	6.08	95	25	100
3	2.40	2.31	59	46	100
4	4.89	2.37	99	87	100
5	3.50	3.06	63	41	100
6	6.45	3.98	100	92	100
7	4.71	1.58	100	42	100
8	1.60	0.84	96	18	97
9	5.91	1.42	93	20	99
10	1.99	1.53	89	32	100
11	3.28	2.65	92	10	87
12	4.09	3.10	94	88	100
13	4.97	2.39	100	41	100
14	0.94	1.17	73	73	100
15	6.05	3.80	97	6	88
16	5.47	3.54	100	49	100
17	0.89	0.91	55	72	100
18	2.63	2.11	74	80	100
Mean	3.98	2.68	88	51	98

*Mean values for electrograms recorded in 1 min. Sep = separation between anterograde (Ante) distribution and retrograde (Retro) distribution; Theta = the angle between mean anterograde vector and mean retrograde vector.

Orthogonal electrograms (Table 2). We next examined the ability of the electrogram vector to discriminate anterograde from retrograde conduction. Examples of typical orthogonal electrograms during anterograde and retrograde conduction and their corresponding vector loops and electrogram vectors are shown in Figure 2A. A plot of elevation versus azimuth for the full minute of anterograde and retrograde recordings is shown in Figure 2B. During anterograde conduction, the values for the electrogram vector tended to cluster closely together. A similar tight cluster of values for the electrogram vector resulted from retrograde conduction. The electrogram vectors during anterograde conduction were significantly different from those during retrograde conduction in all 18 patients ($p < 0.0001$). The angle between mean anterograde and mean retrograde electrogram vectors ranged from 6° to 97° ($50.6 \pm 30.1°$). Of the 18 patients, 14 showed 100% separation between anterograde and retrograde electrogram vector groups; the remaining 4 showed 99%, 97%, 88% and 87% separation, respectively. Combin-

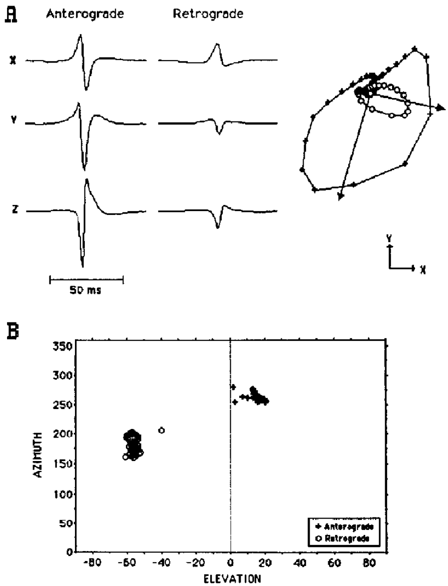


Figure 2. **A,** Patient 2. Examples of typical orthogonal anterograde and retrograde electrograms and their corresponding vector loops. Though the vectors and vector loops are actually calculated in three dimensions, an X versus Y plot is shown here for simplicity (**right**). **B,** Because it is difficult to visually compare the vector distributions during a full minute of anterograde and retrograde electrograms, a plot of elevation versus azimuth yields a more easily analyzed two-dimensional display. Each plus sign represents the elevation and azimuth of a single electrogram during anterograde conduction; each open circle represents the elevation and azimuth of a single electrogram during retrograde conduction.

ing electrogram amplitude and vector did not result in complete separation in these four patients.

Multiple site recordings (Table 3). Five patients had recordings made at multiple sites in the atria. An average of 71 electrograms (range 42 to 92) recorded during anterograde conduction and 99 (range 89 to 119) recorded during retrograde conduction were available for analysis for each site in each of these five patients.

In some patients, the choice of site greatly affected the separation of anterograde from retrograde conduction based on electrogram amplitude. For example, in Patient 11, separation based on amplitude was 52% at the right atrial appendage, 73% at the low right atrium, 92% at the high right atrium and 100% at the low left atrium.

In some patients, the choice of site also greatly affected the separation of anterograde from retrograde vector groups. For example, in Patient 14, the angle between mean electrogram vectors at the high right atrium was 73°, but 152° at the mid right atrium; in Patient 11, percent separation was improved from 87% at the high right atrium to 100% at the right atrial appendage.

Typical electrograms and vector loops from a patient who had simultaneous recordings at two sites in the atria during anterograde conduction and then during retrograde conduction are shown in Figure 3. Note that the order of activation of the two sites is the same during anterograde and retrograde conduction, but the relative timing of activation is different. The corresponding electrogram vectors show that at each site the direction of activation during anterograde conduction is different from that during retrograde conduction.

Additional observations. Atrial electrograms during spontaneous premature atrial complexes were recorded in seven patients during normal sinus rhythm. These electrograms varied widely in amplitude. Those recorded during premature atrial complexes were usually decreased in amplitude, often to within the amplitude range observed during retrograde conduction. The electrogram vectors of premature atrial complexes also varied widely. There was no patient in this small group in whom the electrogram vector of a premature atrial complex overlapped those of the anterograde electrogram vector group. In three patients, the elec-

Table 3. Summary of Atrial Electrogram Data Recorded From Multiple Sites in Five Patients

		Amplitude			Vector	
Patient No.	Site	Ante* (mV)	Retro* (mV)	Sep (%)	Theta (degrees)	Sep (%)
11	HRA	3.28	2.69	92	10	87
	LRA	2.94	2.47	73	86	96
	RAA	4.27	4.27	52	55	100
	LLA	2.74	1.19	100	65	100
12	HRA	4.09	3.10	94	88	100
	RAA	4.79	2.39	100	86	100
14	HRA	0.94	1.17	73	73	100
	MRA	8.06	3.26	100	152	100
15	HRA	6.05	3.80	97	6	88
	MRA	6.27	3.78	100	10	98
18	MRA	2.61	2.10	74	80	100
	LLRA	5.79	4.87	67	78	100

*Mean values for electrograms recorded in 1 min. HRA = high right atrium; LLA = low left atrium (through patent foramen ovale); LLRA = low lateral right atrium; MRA = mid right atrium; RAA = right atrial appendage; other abbreviations as in Table 2.

trogram vectors of one or more premature atrial complexes overlapped or were very close to those of the retrograde electrogram vector group.

Atrial electrograms after spontaneous premature ventricular complexes with retrograde conduction were recorded in two patients. In both cases, the electrogram amplitude decreased to within the amplitude range during retrograde conduction. The electrogram vector was different from those during anterograde conduction in both cases and was quite close to the group of electrogram vectors recorded during paced retrograde conduction.

Discussion

Activation patterns during anterograde and retrograde conduction. The orthogonal catheter has the potential advantage of detecting differences in the direction of wave front propagation and in its timing. In our study, the main goal was to test the ability of the orthogonal catheter to detect differences in the direction of local atrial endocardial activation. Waldo et al. (13,14) studied the pattern of activation in canine and human atria during retrograde conduction and found that the activation sequence can vary greatly, depending on the path of conduction after passage through the AV junction. If the wave front reaches Bachmann's bundle by way of the anterior internodal pathway before the low left atrium, a net high to low atrial depolarization results, similar to anterograde conduction. If the low left atrium depolarizes before Bachmann's bundle, which is often the case, net atrial depolarization is from low to high. We believed that at an appropriate region in the atrium, either of these activation sequences might be different enough from that during anterograde conduction to be detected by the orthogonal catheter.

In patients with a dual-chamber pacemaker, retrograde conduction can cause inappropriate sensing in atrial leads, leading to an "endless loop tachycardia" (15). Previous attempts to discriminate anterograde from retrograde conduction with use of slope (16), configuration, maximal slew rate and amplitude analysis (17) have had varying degrees of success. Recently, Throne et al. (18) reported that template matching using correlation waveform analysis had 100% success in separating short (10-s) data segments. Other pacemaker algorithms for terminating endless loop tachycardia have also evolved (19–21). When this study was

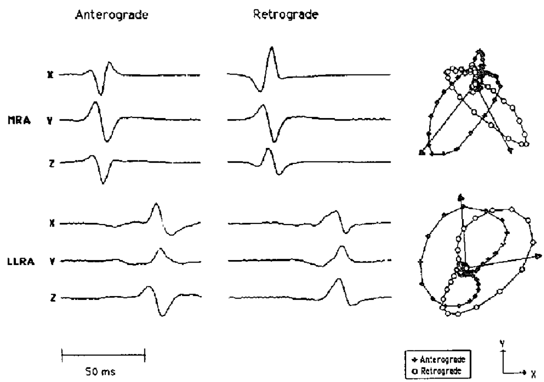


Figure 3. Patient 18. Two orthogonal catheters were placed at the mid (MRA) and low lateral (LLRA) right atrium, respectively, allowing simultaneous recordings at two sites during anterograde and then during retrograde conduction. Typical electrograms (left) and two-dimensional vector loops (right) are shown. Note that the order of activation is the same during anterograde and retrograde conduction, yet at each site, the direction of activation during anterograde conduction is different from that during retrograde conduction.

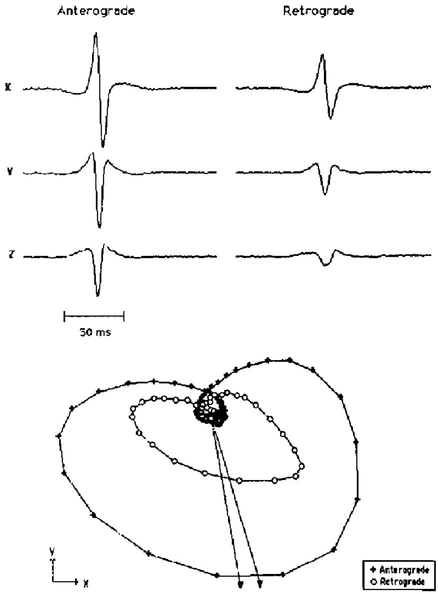


Figure 4. Patient 15. Typical electrograms (top) and two-dimensional vector loops (bottom) from a patient with incomplete separation (88%) of anterograde from retrograde vector distributions. Retrograde conduction was verified by varying paced rate and by confirming constant ventriculoatrial intervals during pacing. Electrogram configuration during anterograde and retrograde conduction is also very similar, yet in this case, electrogram amplitude was an excellent discriminator (97%).

initiated, amplitude discrimination was predominant in published reports. Also, because the electrogram vector is actually a measure of amplitude in three dimensions, we believed that it was sensible to compare the mean vector technique with amplitude discrimination along the traditional bipole.

Standard single bipole. Our data agree with previous work (17) demonstrating that in many cases amplitude sensitivity, which is available in current pacemakers, can decrease inappropriate sensing of retrograde conduction from premature ventricular complexes. In some patients, however, amplitude sensing is ineffective. For example, Patient 17 had only 55% separation of anterograde from retrograde conduction.

The mechanism of the decrease in electrogram amplitude associated with retrograde conduction in our study and others (17) is unknown. Although our data do not explain this mechanism, the electrode to endocardium interface, conduction velocity and wave front cancellation are all variables that could affect electrogram amplitude. The electrode to endocardium interface is held fixed during anterograde and retrograde conduction. Waldo et al. (13) reported that activation of the atria during retrograde conduction consists of several wave fronts. A change in conduction velocity or cancellation of wave fronts, or both, may contribute to the decreased electrogram amplitude recorded during retrograde conduction.

Orthogonal electrograms. The mean separation of anterograde from retrograde conduction (51°) was <180°, the difference one might expect for activation in "opposite" directions. In several patients, a very small angle separated the mean anterograde from the mean retrograde electrogram vector (Fig. 4) and distributions overlapped. These results might also be explained by the data recorded by Waldo et al. (14) during endocardial mapping of the human heart. They found that during paced retrograde conduction, the activation front can often travel rapidly up Bachmann's bundle and then across the sinus node to excite a large portion of the high right atrium in an anterograde fashion. Similar results were also reported in earlier studies by Moore et al. (22). Thus, activation of the high right atrium during anterograde

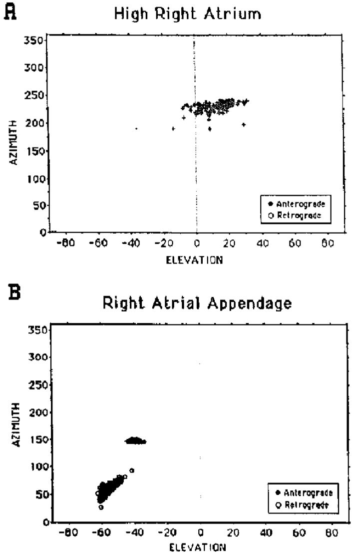


Figure 5. **A,** Patient 11. A plot of elevation versus azimuth shows incomplete separation (87%) of vector distributions recorded at the high right atrium during anterograde and retrograde conduction. **B,** In the same patient, when the catheter is moved to a new site (the right atrial appendage), complete separation of vector distributions results.

and retrograde conduction may be more similar than expected.

The position of the catheter in the high right atrium is also important. It is likely that in some cases, anterograde and retrograde wave fronts may originate from different sites in the atrium yet pass the catheter tip along a similar path. This possibility suggests that there may be a better site than the high right atrium to discriminate between anterograde and retrograde conduction. Such a site could also vary among patients, depending on the path of conduction.

Multiple site recordings. To determine if discrimination of anterograde from retrograde conduction is site dependent, electrograms were recorded from multiple sites in the atria in 5 of the 18 patients. The change in percent separation based on both electrogram amplitude and vector at different atrial sites in some patients verified the hypothesis that discrimination could be site and patient dependent (Fig. 5). This finding tends to reinforce the view that one might have to search for the best site of separation if this technique were used in an implantable device.

Blanchard et al. (23) are experimenting with calculating wave front orientation from a single bipole. Such a procedure would make the vector technique much more practical.

Limitations. There are several limitations to the study. The first is the catheter itself. Standard ring electrodes were used for the x bipole to relate amplitude measurements in that direction with those previously reported. The increased surface area (24) and decreased bipole spacing of these electrodes compared with the circumferential electrodes could skew the measured direction.

Another limitation is the inability to relate sensed direction to anatomic direction. Because we cannot measure the actual direction of endocardial propagation, our justification of the catheter is indirect, based on previously reported patterns of anterograde and retrograde conduction. The tight clustering of values during anterograde and retrograde conduction suggests that the catheter is quite sensitive to changes in the direction of activation, but the absolute measurement of the direction of endocardial activation was not possible in this study. Lastly, should the orthogonal electrode arrangement be implemented in a dual-chamber pacemaker, the effect of pacing on the sensing algorithms is unknown and should be evaluated.

Conclusions. An endocardial catheter with orthogonally placed electrodes can sense changes in the direction of wave front propagation past the catheter tip. As exemplified by its ability to differentiate anterograde from retrograde conduction, such a configuration shows promise for use in examining the direction of activation in different areas of the heart during arrhythmias or conduction abnormalities.

We thank Haris J. Sih for his insightful comments throughout this work, JoEllen Thompson, RN for technical assistance, Mark Paradise for drawing Figure 1 and Shelby J. Haberman, PhD, Chairman, Department of Statistics, Northwestern University for suggestions regarding the statistical methods employed in this study.

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